Modeling the effect of spacers and biofouling on forward osmosis performance

Thesis by

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In Partial Fulfillment of the Requirements

For the Degree of

Master of Science

King Abdullah University of Science and Technology

Thuwal, Kingdom of Saudi Arabia

November, 2014
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ABSTRACT

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*Maria José Mosqueira Santillán*

Currently, the most utilized desalination technology is reverse osmosis (RO), where a membrane is used as a physical barrier to separate the salts from the seawater, using high hydraulic pressure as driving force. A major problem in RO systems is biofouling, caused by severe growth of bacterial biofilms. Both, the need of an external energy input, as well as biofouling, impose a high cost on RO operation.

Forward osmosis (FO) is an alternative membrane process that uses an osmotic pressure difference as driving force. FO uses a concentrated draw solution to generate high osmotic pressure, which extracts water across a semi permeable membrane from a feed solution. One of the main advantages of FO is the limited amount of external energy required to extract water from the feed solution.

The objective of this research is the assessment of the impact of spacers, separating the membrane sheets, and biofouling on the FO system performance. This type of studies allow the optimization of membrane devices and operational conditions. For this, a two dimensional numerical model for FO systems was developed using computational fluid dynamics (CFD). This model allowed the evaluation of the impact of (i) spacers and (ii) biofilm, and (iii) the combined impact of spacers and biofilm on the performance of FO systems.
The results obtained showed that the presence of spacers improved the performance of FO systems. Cavity configuration spacer gave the higher water flux across the membrane in clean systems; whereas for biofouled systems, the submerged configuration showed a better performance. In absence of spacers, the thickness or amount of biofilm is inversely proportional with the water flux. Furthermore, membrane surface coverage of the biofilm is more important than the amount of biofilm in terms of the impact on the performance.

The numerical model can be adapted with other parameters (e.g. membrane and spacer thickness, feed and draw solution, solution concentration, etc.) to predict the impact of biofilm on FO systems under different experimental conditions. The use of numerical modeling may contribute to faster development of economic viable FO based desalination systems.
ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Pascal Saikaly; my committee members, Dr. Johannes Vrouwenvelder, and Dr. Torove Leiknes, for their guidance and support; and my co-advisors Szilárd Bucs, Rodrigo Valladares, and Andrea Radu for their advice along the project.

My appreciation also goes to my friends, Martín, Damián, Cindy, Tsiky, Ali, Claire, and Edward for making my time at King Abdullah University of Science and Technology a great experience.

I also want to extend my gratitude to all the King Abdullah University of Science and Technology Professors and students who were willing to participate in the study.

Finally, my heartfelt gratitude is extended to my parents for their encouragement and to Bruno for his love and support.
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BF   biofilm on the feed side (thickness 150 µm)
BF+  biofilm on the feed side (thickness 300 µm)
BFD  biofilm on the feed and draw sides (thickness 150 µm)
c   concentration
CB   continuous biofilm
CFD  computational fluid dynamics
CP   concentration polarization
cECP concentrative external concentration polarization
ECP  external concentration polarization
EPS  extracellular polymeric substances
DC   discontinuous biofilm
dECP dilutive external concentration polarization
FEM  finite element methods
FO   forward osmosis
ICP  internal concentration polarization
LMH  liter per square meter per hour
M    molarity
MF   microfiltration
NB   no biofilm
NF   nanofiltration
<table>
<thead>
<tr>
<th>NS</th>
<th>no spacer</th>
</tr>
</thead>
<tbody>
<tr>
<td>RO</td>
<td>reverse osmosis</td>
</tr>
<tr>
<td>UF</td>
<td>ultrafiltration</td>
</tr>
<tr>
<td>SC</td>
<td>spacer in cavity configuration</td>
</tr>
<tr>
<td>SS</td>
<td>spacer in submerged configuration</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
</tr>
<tr>
<td>--------</td>
<td>------------------------------------------------</td>
</tr>
<tr>
<td>$A$</td>
<td>water permeability</td>
</tr>
<tr>
<td>$B$</td>
<td>solute permeability</td>
</tr>
<tr>
<td>$c_{\text{draw}}$</td>
<td>draw solute inlet concentration</td>
</tr>
<tr>
<td>$c_{\text{feed}}$</td>
<td>feed solute inlet concentration</td>
</tr>
<tr>
<td>$D$</td>
<td>solute diffusion coefficient in the liquid</td>
</tr>
<tr>
<td>$D_b$</td>
<td>solute diffusion coefficient in the biofilm</td>
</tr>
<tr>
<td>$d_h$</td>
<td>hydraulic diameter</td>
</tr>
<tr>
<td>$D_s$</td>
<td>solute diffusion coefficient in the support layer</td>
</tr>
<tr>
<td>$\Delta c$</td>
<td>concentration difference</td>
</tr>
<tr>
<td>$\Delta \pi$</td>
<td>osmotic pressure difference</td>
</tr>
<tr>
<td>$\Delta P$</td>
<td>hydraulic pressure difference</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>porosity</td>
</tr>
<tr>
<td>$\varepsilon'$</td>
<td>porosity</td>
</tr>
<tr>
<td>$\eta$</td>
<td>water flux through the membrane</td>
</tr>
<tr>
<td>$K_b$</td>
<td>solute permeability in the biofilm</td>
</tr>
<tr>
<td>$L_s$</td>
<td>channel height (along the membrane)</td>
</tr>
<tr>
<td>$L_x$</td>
<td>channel height (along the x-direction)</td>
</tr>
<tr>
<td>$L_y$</td>
<td>channel height (along the y-direction)</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
</tr>
<tr>
<td>--------</td>
<td>-------------------------</td>
</tr>
<tr>
<td>$p$</td>
<td>pressure</td>
</tr>
<tr>
<td>$R$</td>
<td>gas constant</td>
</tr>
<tr>
<td>$Re$</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>$\rho$</td>
<td>liquid density</td>
</tr>
<tr>
<td>$T$</td>
<td>temperature</td>
</tr>
<tr>
<td>$\tau$</td>
<td>tortuosity</td>
</tr>
<tr>
<td>$u$</td>
<td>fluid velocity vector</td>
</tr>
<tr>
<td>$u_{\text{in}}$</td>
<td>average inlet liquid velocity</td>
</tr>
<tr>
<td>$u$</td>
<td>fluid velocity (x component)</td>
</tr>
<tr>
<td>$v$</td>
<td>fluid velocity (y component)</td>
</tr>
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1. INTRODUCTION

1.1 Membrane filtration

A membrane operation is considered a physical process in which a given chemical species or compound can be separated from a stream without any biological or chemical modification. The membrane acts as a selective thin layer which is a physical barrier that completely rejects or reduces the flux of a given chemical species or particle through the membrane so it can be separated from the influent stream. As a result, the influent stream (also called feed) is divided into two different streams: permeate and concentrate. The permeate (also called product) stream contains the chemical species and particles that passed through the membrane; whereas the concentrate refers to the stream that contains the chemical species and particles rejected by the membrane (Fig. 1.1) (Sogaard, 2014).

![Figure 1.1: Scheme of a membrane filtration system. The feed stream containing the compounds 1 (green circles) and 2 (red squares) enters the system. The semi-permeable membrane rejects the compound 2, producing a permeate free of this compound. Adapted from (Vrouwenvelder, 2009).](image-url)
1.2. Classification of membrane processes

Membrane processes can be classified by the driving force, the separation mechanism and/or the membrane rejection properties. The most common way to categorize these processes is by the driving force, this gives two different groups: hydraulic pressure-driven and non-hydraulic pressure-driven membrane processes. The hydraulic pressure-driven processes are those where the driving force is a hydraulic pressure gradient or difference (\( \Delta P \)) across the membrane; examples of these are microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO). On the other hand, the non hydraulic pressure driven membrane processes are those where the hydraulic pressure is not the driving force; examples of membrane processes are the dialysis and forward osmosis (FO), which are osmotically driven membrane processes in which the driving force is directly related to the concentration gradient across the membrane (Table 1.1) (Sogaard, 2014).

Table 1.1: Membrane processes classification (Sogaard, 2014).

<table>
<thead>
<tr>
<th>Hydraulic pressure driven type</th>
<th>Driving force</th>
<th>Non hydraulic pressure driven type</th>
<th>Driving force</th>
</tr>
</thead>
<tbody>
<tr>
<td>microfiltration</td>
<td>hydraulic pressure</td>
<td>dialysis</td>
<td>concentration</td>
</tr>
<tr>
<td>ultrafiltration</td>
<td>hydraulic pressure</td>
<td>electro dialysis</td>
<td>electrical potential</td>
</tr>
<tr>
<td>nanofiltration</td>
<td>hydraulic pressure</td>
<td>forward osmosis</td>
<td>osmotic pressure</td>
</tr>
<tr>
<td>reverse osmosis</td>
<td>hydraulic pressure</td>
<td>membrane distillation</td>
<td>vapor pressure</td>
</tr>
</tbody>
</table>

1.3. Osmosis principle

Osmosis is defined as the net movement of water across a selectively permeable membrane (Vrouwenvelder, 2009). Usually, the selectively permeable membrane rejects the passage of a given solute or ion, while allowing the passage of water molecules. There are two main different osmotic processes: FO and RO. The main difference between them, as stated before, is that the
first one is an osmotically driven process, while the second one is a hydraulic pressure-driven process.

Osmotically driven membrane processes rely solely on the osmotic pressure difference ($\Delta \pi$), which is related with the solute or ion concentration difference ($\Delta c$) across the membrane through the van’t Hoff equation (Hoff, 1887):

$$\pi = RT \cdot \Sigma iM$$

Eq. 1.1

where $R$ is the gas constant, $T$ is the temperature in Kelvin, $i$ is the dimensionless van’t Hoff factor for the specific ion, and $M$ is the molarity of the specific ion.

In FO, the water passes through a semipermeable membrane from a region of low solute concentration to a region of higher solute concentration; while the solute molecules are rejected by the membrane. This process occurs naturally, being the driven force the $\Delta \pi$ between the solutions at both sides of the membrane. As a result, the feed solution is concentrated while the draw stream is diluted. Commonly, osmosis is used as a synonym of FO (Cath et al., 2006).

Figure 1.2: Principle of osmosis and RO (Vrouwenvelder, 2009; Chekli et al., 2012).
In RO systems, the water goes from a region of high solute concentration, to a region of lower solute concentration (Fig. 1.2). This process does not occur spontaneously: and the hydraulic pressure applied to the system. However, the real net driving force in RO operations is a subtraction of $\Delta \pi$ from $\Delta P$ (Qin et al., 2012).

1.4. Reverse osmosis

RO membranes are able to remove mono and divalent ions for more than 99 percent, as well as bacteria, viruses, pesticides, and micropollutants; while allowing water to pass across the membrane. Among the ions that RO membranes are able to reject, are sodium and chloride. This, along with the dramatic improvements in RO technology achieved over the past decades, has elevated RO to be the primary choice for seawater desalination (Greenlee et al., 2009).

One of the major drawbacks in RO technologies is membrane fouling, affecting the performance of the systems (Vrouwenvelder, 2009).

RO membrane fouling

Membrane fouling occurs when dissolved and particulate matter from the feed solution is deposited on the membrane surface during the separation process. Four different types of fouling are considered in membrane filtration systems: inorganic fouling (scaling), organic fouling, colloidal fouling, and biofouling (Flemming, 1997).

The presence of any type of fouling in the system represents a drawback, affecting the performance of the membrane operation by increased pressure drop, decreased water flux, and increased salt passage across the membrane. Different types of fouling may occur
simultaneously, having an accumulative effect on the system performance (Vrouwenvelder, 2009).

In general, fouling can be controlled by pretreatment and chemical dosage (reduction of foulant concentration or tendency in the feed stream) (Characklis and Marshall, 1990). However, while this can be true for the first three types of fouling, i.e. inorganic, organic and colloidal fouling; that is not the case for biofouling (Flemming, 1997).

The major fouling mechanisms in RO membrane systems are scaling, colloidal fouling, and biofouling (Ridway & Flemming, 1996; Vrouwenvelder, 2009). In the Middle East, about 70% of the seawater RO membrane installations suffered from excessive growth of biomass. Also, from 70 surveyed RO installations, 58 reported fouling problems, with biofouling as the predominant operational problem (Vrouwenvelder, 2009).

Biofilms and biofouling

Biofilms are defined as a consortium of bacterial cells embedded in a highly hydrated matrix called extracellular polymeric substances (EPS). EPS consist of proteins, polysaccharides, nucleic acids, lipids and other biopolymers (Flemming & Wingender, 2010). The formation and development of a biofilm usually involves a group of sequential steps which includes the deposition and attachment of the cells on the surface; the substrate uptake and growth of cells; and the detachment and erosion of the biofilm (Fig. 1.3) (Bryers & Ratner, 2004).
Biofilm accumulation affects negatively the performance of RO installations. In several plants, operators struggle with this problem since simple and effective solutions are lacking (Vrouwenvelder, 2009). Biofilm accumulation is commonly related to the biodegradable substrate load (substrate concentration and linear flow velocity) (Bucs et al., 2014).

Biofouling represents one of the most important problems that membrane industry faces. The consequence of biofouling is the reduction in quantity and quality of the product and the subsequent need for expensive chemical cleaning processes and/or ultimately early replacement of the membrane modules, strongly increasing the costs of water production. Because of this, biofouling is considered the Achilles heel of RO membranes operations (Flemming et al., 1997; Al-Juboori and Yusaf, 2012).
Biofouling can be defined as the undesirable accumulation of microbial biofilm on a surface that significantly degrades the equipment performance and/or the equipment lifetime (Fig. 1.4). Biofouling can also be defined as the extent of biofilm formation causing unacceptable operational problems (Characklis and Marshall, 1990). The presence of biofilm alone is not enough to diagnose biofouling, thus biofouling is an operational term. Biofouling diagnosis implies the detrimental impact on the performance of the system, implying the existence of a threshold of interference (Fig. 1.5). The threshold interference may vary from system to system, representing the difference between biofilm and biofouling. Biofilm formation on the membrane represents a problem only when the biofilm formation exceeds a threshold of interference, above which the biofilm formation is defined as biofouling (Flemming, 1997).
Some of the common effects that the presence of biofouling may have in membrane systems are summarized as follows (Flemming, 1997; Vrouwenvelder, 2009):

- decrease of permeate production
- increase of energy consumption
- increase of pressure drop
- increase of resistance to water flux (decrease in water flux)
- inhibition of convectional transport close to the membrane surface
- increase of concentration polarization
- increase in salt passage (decrease in salt rejection)
- increasing cleaning demand
- increased energy costs
- early replacement of the membrane elements (Fig. 1.6)
1.5. Forward osmosis

Currently, RO is the globally most commonly used desalination technology (Frenkel, 2004). However, the energy required during the RO process is high and alternative methods are required that consume less energy. FO has been considered as an alternative that requires less energy input than traditional RO based desalination technologies (Chekli et al., 2012).

In the past ten years there has been a clear growing interest in research in FO operations (Fig. 1.7.), its numerous potential applications can go from water treatment and food processing, to energy generation and novel methods to control drug release (Cath et al., 2006).

Figure 1.7: Annual peer reviewed publications with “forward osmosis” as keyword (Scopus database on: October 2014).
Applications of FO

FO is able to separate a wide range of contaminants and compounds due to a high level of rejection without the need of an external hydraulic pressure. Also, the membranes might be less susceptible for fouling compared to RO, since no hydraulic pressure input for FO is needed. Moreover, FO has a lower demand of electrical energy when compared to hydraulic pressure-driven operations like RO, which makes it a very attractive alternative for RO (Holloway et al., 2007; Qin et al., 2012).

Studies have been made regarding the use of FO membrane systems in the field of industrial wastewater treatment. In general, these studies suggest using the FO operation as a pre-treatment to produce fresh water. Primary treatment with FO can effectively reduce membrane fouling, resulting in lower costs (Zhao et al., 2012).

Additionally, FO membrane systems have been studied for the desalination of saline water. Two different types of desalination processes are known. The first type of desalination using FO involves the osmotic dilution of the concentrated draw solution, and the subsequent generation of fresh water from this draw stream. In the second type, the FO process acts as the pre-treatment before an RO or NF process (Fig. 1.8)(Zhao et al., 2012).
Figure 1.8: Integrated FO-NF system for seawater desalination (Tan and Ng, 2010).

FO has been studied for the concentration of water-containing food, functioning as a dehydration process in the food industry. Typically, the dehydration process is achieved by evaporative concentration that uses high temperatures, which can modify the physical and chemical properties of the processed food. Advantages of FO include the operation at low temperatures, meaning lower costs and the possibility of better preservation of the food quality, taste, aroma, and nutritional value (Petrotos and Lazarides, 2001).

FO technology has also profited the pharmaceutical industry. In this sector, two types of applications have been found for FO processes. The first application is in the osmotic drug delivery; while the second one involves the enrichment of pharmaceutical products, many of which are known to be heat sensitive (Herbig et al., 2000; Santus and Baker, 1995).

Besides the already mentioned applications, additional uses for FO processes have been proposed in the fields of energy, agriculture, and environment. However, FO is still considered an emerging technology, and a lot of research is needed (Zhao et al., 2012).
Concentration polarization in FO

FO membranes have an asymmetric structure, consisting of a thin active layer that is responsible for the separation process; and a thick support layer of porous polymer providing mechanical stability to the active layer. For FO operations, the active layer faces the feed solution, while the support layer is directed against the draw solution side (McCutcheon and Elimelech, 2007).

One consequence of the asymmetry of the FO membranes used in FO is a phenomenon known as concentration polarization (CP). In FO, as well as in other osmotically driven membranes processes, the CP is caused by the solute concentration difference ($\Delta c$) between the feed and draw solutions. CP is a membrane-associated transport phenomenon in which the $c$ at the membrane-solution interfaces is much different than the bulk solution. The generation of a polarized boundary layer on the surface of the active layer can effect the membrane performance, specifically regarding the water flux through the membrane, which is reduced due to this phenomenon, increasing the probability of scale development (Lee, et al., 1981; Cath et al., 2006; Zhao et al., 2012).

CP in FO can be classified in three types: concentrative external concentration polarization (cECP), dilutive external concentration polarization (dECP), and internal concentration polarization (ICP) (Table. 1.2 and Fig. 1.9).

Table 1.2: Classification of CP processes in FO systems.

<table>
<thead>
<tr>
<th>concentration polarization (CP)</th>
<th>internal concentration polarization (ICP)</th>
<th>external concentration polarization (ECP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>characteristic</td>
<td>location</td>
<td>characteristic</td>
</tr>
<tr>
<td>dilutive ICP</td>
<td>support layer of the membrane</td>
<td>concentrative ECP (cECP)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>dilutive ECP (dECP)</td>
</tr>
</tbody>
</table>
External concentration polarization (ECP) occurs in both sides of the membrane, this means, in the active layer-feed solution and the support layer-draw solution interfaces. In the first case the feed solution flows through the membrane while the salt is rejected, as a consequence, the salt concentration in the vicinity of the membrane is higher than that in the bulk feed solution; this CP process is defined as cECP. Simultaneously, the permeated water that flows through the membrane from the feed side to the draw solution reduces the concentration of salt in the vicinity of the support layer, this is known as dECP. As both types of ECP occur simultaneously at the two surfaces of the membrane, they can be alleviated or mitigated by e.g. altering the hydrodynamic conditions in the feed and draw channels (Cath et al., 2006; Zhao et al., 2012). An approach to alter the hydrodynamic conditions in the channels of the system is the use of plastic mesh spacers (Fig. 1.10). It has been reported in the literature that the spacers can induce turbulence and alter the mass transfer patterns in a membrane channel (Song and Ma, 2005; McCutcheon and Elimelech, 2006).

![Figure 1.9: Concentration polarization phenomena occurring in a FO membrane (Qin et al., 2012).](image)

Figure 1.9: Concentration polarization phenomena occurring in a FO membrane (Qin et al., 2012).
ICP refers to the CP that occurs within the support layer. In FO systems the water permeates the membrane from the feed side to the draw side, as a result, a dilutive ICP phenomenon takes place where the draw solution within the porous support layer becomes diluted. As ICP occurs within the confines of the support structure, its impact on the performance of the system cannot be alleviated by increasing the flow velocity or turbulence in the channels. In fact, this is the main reason why ICP is considered a key performance-limiting factor (Gray et al., 2006).

ICP is considered one of the most important phenomena in FO and other osmotically driven membrane operations, hampering the performance of the system. Hence, a better understanding of ICP can lead to the development of different ways to improve FO processes by optimizing membrane characteristics and system parameters (Cath et al., 2006; McCutcheon and Elimelech, 2007; Zhao et al., 2012).
Biofouling in FO

All membrane filtration systems are in contact with microorganisms, thus they are susceptible to biofouling, so the membrane elements have to be cleaned and in the worst case early replaced. Biofouling occurs when biodegradable nutrients in the water flow are available for microorganisms (Flemming et al., 1997; Valladares Linares et al. 2014). This means that not only the RO membrane installations, but also the FO membranes systems are prone to this problem.

FO processes are considered an emerging technology. The effect of biofilm formation on the membrane surfaces of FO systems is not yet well understood. Thus, it is important to study the impact of biofouling on FO membrane performance.

Computational fluid dynamics in forward osmosis

During the last 15 years, computational fluid dynamics (CFD) have become increasingly popular to better understand and study the behavior and complexity of the phenomena taking place in membrane systems. CFD have become an attractive tool in the membrane industry when compared to invasive, and other non-invasive methods as it helps minimizing the number of experiments and allows researchers to achieve the goal of better designs cost and time effectively. Moreover, CFD also provide a robust approach capable of including and manipulating many interacting parameters and different geometries (Ghidossi et al., 2006; Gruber et al., 2011; Park and Kim, 2013).

There are several predictive models that have been developed using CFD to study membrane systems (Song and Ma, 2005, Ghidossi, 2006; Fimbres-Weihs and Wiley, 2010). In the case of FO operations, several one dimensional and two dimensional models have been developed and many of these have proved to accurately predict the membrane performance over some limited
ranges (Lee et al., 1981; Loeb et al., 1997; Ghidossi et al., 2006; Gray et al, 2006; McCutcheon and Elimelech, 2007; Tan and Ng, 2008; Gruber et al., 2011; Li et al., 2011; Park et al., 2011; Sagiv and Semiat, 2011; Park and Kim, 2013).

The developed models for FO systems focus on the hydrodynamics and mass transport of solutes. Simulations have been made on the effects of CP on the membrane performance (McCutcheon and Elimelech, 2007; Gruber et al., 2011; Sagiv and Semiat, 2011); or the impact of the support layer on the ICP (Li et al., 2011). Only two models consider the presence of spacer in FO systems. Ghidossi et al. (2006) study the role of spacers as turbulence promoters in single channel systems; while Park and Kim (2013) study the local impact of spacers on ECP in the feed channel.

However, all of the models in literature consider a clean FO system, were no biomass is attached to the membrane. Therefore, a systematic numerical approach is needed to analyze the presence of biofilm in FO systems and how affects the membrane performance.
2. OBJECTIVE

The objective of this work is to develop a two dimensional numerical model to assess the impact of the presence of spacers and biofilm on the performance of an FO system. Different studies were done to assess the impact on FO performance of (i) spacers, (ii) biofilm, (iii) biofilm membrane surface coverage, and (iv) spacers and biofilm combined.

The model developed will be the first of its kind as no numerical model for FO membrane systems has been reported that includes the presence of biofilm and its impact on the system performance.
3. MODEL DESCRIPTION

A two dimensional numerical model was developed to assess the impact of spacer and biofilm on performance in a FO system. The model was implemented in a commercially available CFD software (COMSOL 4.4, Comsol Inc., Burlington, MA, www.comsol.com) based on finite element method (FEM). The developed model consists of hydrodynamics and solute transport in free channels and porous media.

3.1. Model geometry

The developed model considers a flat sheet membrane separating the feed and draw channels. The length of the channels is chosen to be of 1 cm ($L_x$) for computational reasons. The feed and draw channels are 1.17 mm ($L_y$) height. The channel height is corresponding to 46 mil (1 mil = 25.4 µm) spacer commonly used in practice for FO processes (Table 3.1). For this model an asymmetric membrane is considered, separating the feed from the draw channel. The membrane is comprised of a 50 µm support layer and a zero thickness active layer. The active layer of the membrane is facing the feed channel, representing FO configuration.

The model geometry consists of two domains ($d_1$, $d_2$), where domain $d_1$ and $d_2$ are the feed and draw channels respectively. The draw channel is divided in two subdomains: bulk liquid ($d_{2.1}$) and the membrane ($d_{2.2}$). In this model the support layer of the membrane is considered as a subdomain, whereas the active layer is modelled as a line without thickness. For cases with biofouling, the domains where the biofilm is located are separated into subdomains. Spacer filaments, separating the membrane sheets are represented as circles and subtracted from the feed and draw domains. The subtracted areas are not considered as separate domains in this model (Fig. 3.1).
Table 3.1: Parameters used for the FO membrane numerical simulations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model geometry</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>channel length</td>
<td>$L_x$</td>
<td>0.01</td>
<td>[m]</td>
<td>chosen</td>
</tr>
<tr>
<td>channel height</td>
<td>$L_y$</td>
<td>1.17</td>
<td>[mm]</td>
<td>(Valladares Linares et al., 2014)</td>
</tr>
<tr>
<td>membrane thickness</td>
<td>$L_s$</td>
<td>50</td>
<td>[µm]</td>
<td>(Valladares Linares et al., 2014)</td>
</tr>
<tr>
<td>spacer thickness</td>
<td>-</td>
<td>0.58</td>
<td>[mm]</td>
<td>chosen</td>
</tr>
<tr>
<td>spacing between spacer filaments</td>
<td>-</td>
<td>4.5</td>
<td>[mm]</td>
<td>(Park and Kim, 2013)</td>
</tr>
<tr>
<td><strong>Physical parameters</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>average inlet liquid velocity</td>
<td>$u_{in}$</td>
<td>0.1</td>
<td>[m·s$^{-1}$]</td>
<td>(Valladares Linares et al., 2014)</td>
</tr>
<tr>
<td>liquid density</td>
<td>$\rho$</td>
<td>1000</td>
<td>[kg·m$^{-3}$]</td>
<td>(Bucs et al., 2013)</td>
</tr>
<tr>
<td>liquid viscosity</td>
<td>$\eta$</td>
<td>$10^{-3}$</td>
<td>[Pa·s]</td>
<td>(Bucs et al., 2013)</td>
</tr>
<tr>
<td>feed solute inlet concentration</td>
<td>$c_{feed}$</td>
<td>0.034</td>
<td>[mol·L$^{-1}$]</td>
<td>(Valladares Linares et al., 2014)</td>
</tr>
<tr>
<td>draw solute inlet concentration</td>
<td>$c_{draw}$</td>
<td>0.68</td>
<td>[mol·L$^{-1}$]</td>
<td>(Valladares Linares et al., 2014)</td>
</tr>
<tr>
<td>solute diffusion coefficient</td>
<td>$D$</td>
<td>$10^{-9}$</td>
<td>[m$^2$·s$^{-1}$]</td>
<td>(Park and Kim, 2013)</td>
</tr>
<tr>
<td><strong>Membrane properties</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>porosity</td>
<td>$\varepsilon$</td>
<td>0.7</td>
<td>-</td>
<td>(Sagiv and Semiat, 2011)</td>
</tr>
<tr>
<td>water permeability</td>
<td>$A$</td>
<td>1.2</td>
<td>[L·m$^{-2}$·h$^{-1}$·bar$^{-1}$]</td>
<td>(Park and Kim, 2013)</td>
</tr>
<tr>
<td>solute permeability</td>
<td>$B$</td>
<td>0.5</td>
<td>[L·m$^{-2}$·h$^{-1}$]</td>
<td>(Park and Kim, 2013)</td>
</tr>
<tr>
<td>solute diffusion coefficient</td>
<td>$D_s$</td>
<td>$D \times \varepsilon/\tau$</td>
<td>[m$^2$·s$^{-1}$]</td>
<td>(Saripalli et al., 2002)</td>
</tr>
<tr>
<td>ratio between membrane porosity</td>
<td>$\varepsilon/\tau$</td>
<td>0.02</td>
<td>-</td>
<td>(Saripalli et al., 2002)</td>
</tr>
<tr>
<td>and tortuosity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Biofilm properties</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>porosity</td>
<td>$\varepsilon_b$</td>
<td>0.8</td>
<td>-</td>
<td>(Radu et al., 2010)</td>
</tr>
<tr>
<td>permeability</td>
<td>$K_b$</td>
<td>$10^{-16}$</td>
<td>[m$^3$]</td>
<td>(Radu et al., 2010)</td>
</tr>
<tr>
<td>solute diffusion coefficient</td>
<td>$D_b$</td>
<td>$D \times 0.8$</td>
<td>[m$^2$·s$^{-1}$]</td>
<td>chosen</td>
</tr>
</tbody>
</table>
Figure 3.1: Modeled FO geometry. (a) Feed and draw channels (d1 and d2 respectively), spacer filaments (white circles). (b) Zoom in: active layer (red line), support porous layer (d2.2), biofilm (d1.2), feed bulk solution (d1.1), and draw bulk solution (d2.1). The model dimensions $L_x$, $L_y$ and $L_s$ are presented in table 3.1.
Spacer configuration

Two spacer configurations were evaluated, cavity and submerged. The cavity configuration results from a cut through of a non woven spacer, where the axial and transversal filaments have the same thickness (Fig. 3.2a). The submerged configuration results from a cut through of a non-woven spaghetti like spacer with different filament thicknesses (Fig. 3.2b).

Two dimensional representation of three dimensional structures results in loss of details. In the developed model this translation resulted in simulation of only one set of spacer filaments. Although only one of the filaments is considered, the channel height considers the presence of both filaments.

![Figure 3.2: Schematic view of spacer configurations used in the model. Three-dimensional spaghetti like spacer and two-dimensional cross section, cavity spacer (a), three-dimensional middle layer spacer and two-dimensional cross section, for the submerged spacer configuration (b).](image)

Biofilm arrangement

The biofilm was represented as subdomain of the feed or draw channel. The biofilm subdomains were considered as porous media. Three different biofilm arrangements were evaluated, differing in thickness and/or membrane surface coverage. Biofilm with 80 percent membrane surface coverage is considered as continuous biofilm. The continuous biofilm thickness was
varied from 150 μm to 300 μm (Fig. 3.3a,b). The discontinuous biofilm covers 40 percent of the membrane surface with various thicknesses, and randomly distributed over the membrane length (Fig 3.3c).

![Figure 3.3: Biofilm arrangements used in the numerical model. Continuous thin layer (a) and two fold thicker (b) biofilm, covering 80 percent of the membrane active layer and discontinuous biofilm (c) with the same biofilm volume as the continuous thin layer biofilm (a) but covering 40 percent of the membrane active layer.](image)

3.2. Liquid flow and solute transport

**Liquid flow**

Fimbres-Weihs and Wiley (2007) showed that the water flow in feed channels with spacers is laminar up to a Reynolds number (Re) of 200 for spacers, but becomes unsteady for Re between 200 and 300. The Re numbers were computed according to Schock and Miquel (1987).

\[
Re = \frac{\rho \cdot u \cdot d_h}{\eta}
\]

Eq. 3.1

where \( \rho \) is the fluid density (kg/m\(^3\)), \( u \) is the fluid velocity (m/s), \( d_h \) is the hydraulic diameter (m) and \( \eta \) is the dynamic viscosity of the fluid (Pa × s).
For all spacer configuration Re was less than 200, therefore the Navier–Stokes equations were used to model the laminar, incompressible and stationary flow which was assumed for all simulation:

\[
\rho \cdot (\mathbf{u} \cdot \nabla) \cdot \mathbf{u} + \nabla p = \nabla \cdot (\eta \nabla \mathbf{u}), \quad \nabla \cdot \mathbf{u} = 0
\]

Eq. 3.2

where \( \mathbf{u} \) is the fluid velocity vector (m/s), and \( p \) refers to the pressure (Pa).

Fully developed laminar flow was assumed at the inlet \( x = 0 \) for the feed channel and \( x = L_x \) for the draw channel, with the average fluid velocity \( u_{in} \). On the outlet boundary at \( x = L_x \) for the feed channel and \( x = 0 \) for the draw channel, zero pressure (arbitrarily chosen as reference value) and no viscous stress conditions were imposed. The feed channel bottom and draw channel top edges (\( y = 0 \) and \( y = 2xL_y + L_s \)), as well as the spacer perimeters were considered as no-slip walls (Fig. 3.4a).

The liquid velocity through the membrane is the velocity component \( v \) (normal to the membrane), which takes variable values at different positions \( x \) along the membrane length. At the active layer of the membrane, the tangential velocity \( u \) is set to zero. This results in the following boundary conditions on the membrane active layer:

\[
u(x, 0) = 0, \quad v(x, 0) = A(c_{draw} - c_{feed})2 \cdot R \cdot T
\]

Eq. 3.3

The local permeate flux, \( v \), is proportional with the osmotic pressure \( \Delta \pi \) created by the concentration difference between the two sides of the membrane. The osmotic pressure difference is proportional (osmotic coefficient \( A \)) to the salt concentration difference at the two sides of the membrane. For numerical stability reasons, transition zones were created near inlet \((x = [0, 0.02 \cdot L_x])\) and outlet \((x = [0.98 \cdot L_x, L_x])\), where the membrane permeability was
allowed to change from zero to A. Flux continuity applies on the biofilm-liquid interface (Fig. 3.4a).

Solute transport

The salt (NaCl) is assumed to be the only soluble compound relevant for the scope of this study. The mass balance for salt (concentration $c$) in the channels includes transport by convection and diffusion:

$$u \nabla c = D \nabla^2 c$$

Eq. 3.4

where $c$ is the salt concentration (mol/L) and $D$ is the solute diffusion coefficient (m$^2$/s). The diffusion coefficient $D$ depends on the local concentration $c$, however, due to the very low concentrations of the solute the diffusion coefficient $D$ is considered constant. The diffusion coefficient in the membrane support layer and biofilm subdomains were considered different as in the bulk liquid (Table 3.1).

Initial concentrations $c_{feed} = 0.034$ mol/L and $c_{draw} = 0.68$ mol/L for the feed ($x = 0$) and draw ($x = L_x$) channels are imposed as inflow conditions. The outlet boundary (feed $x = L_x$ and draw $x = 0$) are set as an open outflow. The feed channel bottom and draw channel top edges ($y = 0$ and $y = 2\times L_y + L_s$), as well as the spacer perimeters were considered as no flux (Fig. 3.4b).

Solute from the draw channel to the feed channel is diffusing through the active layer ($y = L_y$) of the membrane,

$$J_s = B(c_{draw} - c_{feed})$$

Eq. 3.5

where $J_s$ is the salt passage through the membrane and $B$ is the membrane solute permeability coefficient (L/m$^2$/h). Flux continuity applies on the biofilm-liquid interface (Fig. 3.4b).
Figure 3.4: Boundary conditions used in the model: for liquid flow (a) and solute transport (b) in the feed, biofilm, membrane, and draw channels.

3.3. Model solution

The feed and draw channels and subdomains are defined, together with the model equations and the boundary conditions for the geometry. For this, the following COMSOL application modes were constructed: (i) incompressible Navier–Stokes for momentum transport, and (ii) convection and diffusion for mass transport of salt.

The finite element mesh is created with the specifications for maximum element size of 5 \( \mu m \) in the subdomain and on the membrane boundaries. A nonuniform mesh is needed to obtain accurate numerical solutions for mass transfer due to high concentration gradients near the membrane. Preliminary simulations established that a minimum mesh size of 5 \( \mu m \) on the
membrane surface is sufficient for mesh convergence (Radu et al., 2010). The mesh size is increased towards the bulk liquid up to a maximum of 30 μm (Fig. 3.5).

![Image](image.png)

**Figure 3.5:** Detail of the finite element mesh used in the model. The mesh was utilized to solve the hydrodynamics and mass transport equations. The mesh size of 5 μm on the boundaries was increased towards the bulk liquid to a maximum of 30 μm.

The liquid flow equation (Eq. 3.2) is solved separately to get \( \mathbf{u} \) and \( p \). This initial step was introduced to reduce the computational power and increase numerical stability. On a second step, the mass balance for salt equations (Eqs. 3.4 and 3.5) are coupled with the liquid flow equations (Eq. 3.2 and 3.3) using as initial condition the vector field \( \mathbf{u} \) computed previously. A fully coupled approach is needed because the water flux trough the membrane \( J_s \) depends on the salt concentration \( c \), which in turn is influenced by the flow.

### 3.4. Data visualization and interpretation

Calculations of water flux with the two dimensional model, result as flux velocity across the membrane. These results are related to membrane surface by integration of the water flux...
velocity profile along the membrane active layer. Results are presented as rate of the water flux per membrane area in time.

Due to high salt concentration differences between the draw and feed solutions the changes in concentration near the membrane surface or in the biofilm are not visible on simple plots. For better understanding and quantification of CP (cECP and ICP) the concentration difference ($\Delta c$) between average solute concentration at the membrane active layer and bulk liquid is calculated. The absolute values of the salt concentration differences are presented in bar graphs and considered as an indicator for CP.
4. RESULTS

A two dimensional numerical model was developed to evaluate the impact of spacer and biomass accumulation on performance of FO membrane systems. The studies evaluated the impact of (i) different spacer configurations, (ii) amount of biofilm, (iii) membrane surface coverage by the biofilm, and (iv) combined spacer and biofilm presence (Table 4.1).

**Table 4.1: Overview of studies.**

<table>
<thead>
<tr>
<th>Study</th>
<th>Spacer</th>
<th>Biofilm</th>
<th>Biofilm thickness</th>
<th>Surface coverage</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impact of spacer</td>
<td>no</td>
<td></td>
<td>-</td>
<td>0%</td>
<td>4.1</td>
</tr>
<tr>
<td>cavity configuration</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>submerged configuration</td>
<td>No</td>
<td>-</td>
<td>0%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Impact of biofilm</td>
<td>no</td>
<td></td>
<td>150 µm</td>
<td>80%</td>
<td>4.2.1</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>300 µm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Impact of membrane surface</td>
<td>no</td>
<td></td>
<td>150 µm</td>
<td>80%</td>
<td>4.2.2</td>
</tr>
<tr>
<td>coverage by biofilm</td>
<td>continuous thin layer</td>
<td>various</td>
<td>40%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>discontinuous thin layer</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combined impact of</td>
<td>no</td>
<td></td>
<td>150 µm</td>
<td>80%</td>
<td>4.3</td>
</tr>
<tr>
<td>spacer and biofilm</td>
<td>cavity configuration</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>submerged configuration</td>
<td>no</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>yes</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.1. Impact of spacer on performance

Impact of spacer presence and location on flux

To study the impact of spacer on the water flux across the membrane and CP, numerical
simulations were run without (NS) and with spacer. With spacer, two different configurations
were evaluated: cavity (CS) and submerged (SS), differing in the location in relation to the
membrane (Fig. 3.2). Both sides of the membrane had the same spacer configuration.

Without spacer, a stable water flux was found over the membrane (Fig. 4.1). With spacer in
submerged configuration, a similar flux profile was observed compared to without spacer,
increasing slightly the flux after the spacer filament (red arrow in Fig. 4.1). The spacer in cavity
configuration showed (i) a higher flux over the membrane and (ii) a much lower local flux where
the spacer filament was in contact with the membrane (blue arrow in Fig. 4.1). The local water
flux across the membrane was affected by the location of the spacer.

Figure 4.1: Impact of spacer on local water flux across the membrane for the studied system
without biofilm. Simulations were run without spacer (NS), with spacer in cavity (SC) and
submerged (SS) configuration.
Concentration polarization

To study the CP processes in the FO system, an imaginary vertical line is defined across the three computational domains: feed side, draw side, and membrane (Fig. 4.2). The line section from I to II involves the feed side, section from II to III involves the membrane, and section from III to IV covers the draw side. These labels (I-IV) will be used in the following figures and text. The imaginary line was used to plot the salt concentration profile in the vicinities and in the support layer of the membrane (Fig. 4.3).

![Image](image_url)

**Figure 4.2:** Imaginary line used to evaluate CP. Line covering the feed side of the membrane (I to II), line crossing the membrane between points (II to III), and line in the draw side of the membrane (III to IV).

The numerical model showed the occurrence of cECP at the membrane feed side (Fig. 4.3, I to II), whereas dECP was found on the draw side (Fig. 4.3, III to IV). In the porous layer of the membrane a non-linear ICP profile was observed (Fig. 4.3, II to III, coloured rectangle).

A small solute concentration increase was found in the vicinity of the active layer of the membrane (Fig. 4.3, I to II). However because of the high difference in salt concentration between the feed and draw solutions it is difficult to visualize the cECP at this scale. For visualization purposes and analysis of the results, each type of CP is presented separately in the
following sections. For FO systems the cECP and ICP have a stronger impact on performance than dECP. Thus, only cECP and ICP were evaluated.

**Figure 4.3**: Calculated salt concentration profile without spacer and without biomass accumulation along the imaginary line (I to IV). The three types of concentration polarization (CP) occur in FO systems: concentrative external concentration polarization (cECP), internal concentration polarization (ICP), and dilutive ECP (dECP). The blue rectangle represents the support layer of the membrane with the active layer at the left (red line); the locations of cECP, ICP and dECP are indicated using arrows. The water flux occurs from left to right.

The solute concentration at the feed side of the membrane increased towards the membrane (Fig. 4.4a, I to II). Inside the membrane support layer, the solute concentration decreased over the membrane thickness for all cases compared to the draw solution, causing severe ICP (Fig. 4.4b, II to III). This was found for the three different scenarios: system without spacers (NS) and with spacers in cavity (SC) and submerged configuration (SS). In other words, both cECP and ICP showed a similar trend and magnitude for the cases without and with spacer.
The line graphs shown so far are useful to understand the local impact of spacers on water flux and CP. However, to better evaluate the impact of the spacer on membrane performance the data are presented in a bar graph (Fig. 4.5).

The use of spacer increased the water flux across the membrane (SS and SC in Fig. 4.5a). The use of cavity spacer enabled a higher water flux than with submerged spacer and without spacer.
The cavity spacer had the lowest ICP and highest cECP (SC in Fig. 4.5b,c). As observed with the cavity spacer, the cECP had no large impact on the water flux since the highest water flux was achieved using the cavity spacer.

4.2. Impact on biofilm on performance

4.2.1. Effect of biofilm presence and thickness

In the previous section the FO performance was studied with and without spacers and without biofilm. To assess the effect of biofilm on FO performance, studies were done without biofilm (NB), and with two biofilms differing in thickness (BF and BF+, where BF+ has a twofold biofilm thickness compared to BF). The studies were done in the absence of spacers and the biofilm was located on the membrane feed side covering 80 percent of the membrane surface.

Without biofilm, a stable water flux was found over the membrane (NB in Fig. 4.6). At the biofilm location, a decline of flux was observed compared to without biofilm. With a twofold thicker biofilm (BF+), a stronger flux decline was found (Fig. 4.6, BF and BF+). Doubling of the biofilm amount was not doubling the flux decline (Figs. 4.6, 4.7a). With biofilm, a higher water flux was found on the membrane not covered by the biofilm compared to the system without biofilm (Fig. 4.6). The higher biofilm amount on the membrane increased the ICP (Fig. 4.7b) and cECP (Fig. 4.7c). Clearly, the biofilm presence reduced the water flux and increased concentration polarization in the absence of a spacer.
Figure 4.6: Impact of the biofilm thickness on the local water flux for the studied system without spacer. Simulations were run without biofilm (NB), with a thin layer of biofilm (BF) and a twofold thicker biofilm (NF+).

Figure 4.7: Impact of biofilm on water flux (a), ICP (b), and cECP (c). Simulations were run without biofilm (NB), using a thin layer of biofilm (BF) and a twofold thicker biofilm (BF+).
4.2.2. Effect of biofilm surface coverage

To determine the impact of membrane surface coverage by the biofilm on FO performance, a numerical modeling study was done with a continuous biofilm (CB, covering 80 percent of the membrane surface), and a discontinuous biofilm (DB, covering 40 percent of the membrane surface). Both biofilms were located on the membrane feed side and had the same volume.

The presence of biofilm had a local impact on water flux (Fig. 4.8). The water flux decreased sharply at the locations of the membrane active layer in direct contact with the biofilm. The same amount of biomass discontinuously distributed had a higher water flux (Fig. 4.9a). The discontinuously distributed biofilm showed a lower ICP (Fig 4.9b) and cECP (Fig. 4.9c). Evidently, the surface coverage by biofilm plays a more important role on FO performance than the biomass amount.

![Figure 4.8: Impact of surface coverage by biofilm on the local water flux for the studied FO system without spacer. Simulations were run without biofilm (NB), with a continuous biofilm (CB), and a discontinuous biofilm (DB). Both types of biofilm had the same total biomass volume.](#)
Figure 4.9: Impact of biofilm surface coverage of FO membrane on water flux (a), ICP (b), and cECP (c). Simulations were run without biofilm (NB), a continuous biofilm (CB), and a discontinuous biofilm (DB) with 50 percent lower membrane surface coverage. Both types of biofilm had the same total biomass volume.

4.3. Combined impact of spacer and biofilm on performance

To determine the impact of both spacers and biofilm on FO performance a numerical modeling study was done without biofilm (NB), with biofilm on the feed side (BF), and with biofilm on both sides of the membrane (BFD). Simulations were run without spacer (NS), and with spacer in cavity (SC) and submerged (SS) configuration. All biofilms had the same total volume.

Effect on flux

The flux in FO systems was decreased by the presence of a biofilm on the feed side, regardless the presence and configuration of the spacer (Fig. 4.10a, BF compared to NB). The flux decrease was stronger when a biofilm was present on both sides of the membrane (Fig. 4.10a, BFD compared to BF). The use of spacers in cavity configuration improved the water flux in clean systems, but decreased the flux in biofouled systems (Fig. 4.10a).
Effect on CP

The ICP was higher with the presence of a biofilm on the feed side when compared to the system without biofilm (Fig. 4.10b, BF compared with NB). The biofilm without spacer had a slightly lower ICP than with spacer (Fig. 4.10b, BF). These findings indicate that the biofilm has a higher impact on CP than the spacer. Biofilm presence on both sides of the membrane increased the ICP compared to the biofilm present on the feed side only (Fig. 4.10b, BFD compared to BF).

For both without spacer and with submerged spacer a low value was found for cECP in the absence of a biofilm, while a high cECP value was found for the cavity spacer (Fig. 4.10c, NB). A similar trend is found for the systems with biofilm on the feed side and on both sides of the membrane (Fig. 4.10c BF and BFD). Remarkable is the observation that the system with biofilm has a lower ECP in the system with cavity spacer than in the one without spacer or spacer in submerged configuration. The submerged spacer showed a low water flux in a clean system, but...
the highest water flux in the biofouled system, underlining the importance of studies integrating design (spacer) and fouling (biofouling).
5. DISCUSSION

The objective of this work was to develop a two dimensional numerical model for forward osmosis (FO) membrane system, to assess the impact of the presence of spacers (cavity and submerged configuration) and biofilm on system performance.

Both, biofilm and spacers affected the local water flux across the membrane (Figs. 4.1, 4.6, 4.8). Among the spacers, cavity configuration had a higher local impact than submerged spacers. Cavity spacers disrupted abruptly the local flux by generating dead zones at the location of spacer attachment to the membrane (Fig. 4.1).

For clean systems, the ICP served as an effective indicator of the performance of the system, having an inversely proportional relationship with water flux across the membrane. As observed with the cavity spacer, the ICP has a higher impact than cECP on the performance of the system (Fig. 4.5a,b,c).

In clean systems, spacers in cavity configuration showed the best system performance. Whereas for biofouled systems, the submerged configuration showed the highest water flux across the membrane (Fig. 4.10a).

In the absence of spacer, thin biofilms yielded a higher water flux and lower CP than thicker biofilms (Fig. 4.7a,b,c). Regardless of the total biofilm amount, the surface coverage plays an important role on the performance of the system, by decreasing the CP and increasing the flux across the membrane (Fig. 4.9a,b,c).
5.1. Model evaluation

The simulations showed similar findings when comparing with recently published numerical studies which emphasize the importance of spacers in alleviating CP and improving the performance of FO systems (Ghidossi et al., 2006; Park and Kim, 2013). It was reported that submerged spacer configuration has a better performance than spacer in cavity configuration (Park and Kim, 2013). Our developed model showed better performance when cavity configuration is used. Nevertheless, the nonrealistic parameters used for Park and Kim (2013) numerical model (1 mm membrane thickness) can affect the results, as it has been shown by our and their model that there is a high sensitivity for changes in membrane parameters. This matches with previous studies where it has been suggested that the development of high performance membranes may have a higher impact on the performance of FO systems than optimization of operating conditions such as the inlet flow velocity (Park et al., 2011).

Comparing with experimental data, it was found that the calculated water flux for the system without biofouling was 1.07% different than the experimentally measured water flux in clean systems (Valladares Linares et al. 2014).

The developed two dimensional numerical model, described well existing experimental observations (Valladares Linares et al. 2014) and is comparable with previously published models for FO systems (Sagiv and Semiat, 2011; Park and Kim, 2013).

5.2. Comparison of FO with RO

The results found can be compared with literature in modeling of RO systems. Regarding the impact of spacers on the performance of clean systems, different results have been found.
While some studies state that submerged spacer configuration give the best performance (Radu et al., 2010), other studies report that cavity configuration alleviates ECP, generating a higher water flux and thus, a better performance of clean RO systems (Geraldes et al., 2002; Ma and Song, 2006). According to our results, cavity spacers are also beneficial for the performance of the FO system. However, our simulations indicate that the use of cavity spacers simultaneously improves the performance and increases the ECP in FO systems, supporting the higher importance of ICP over ECP in FO operations.

For biofouled RO systems, studies have found that among the different spacer configurations, submerged spacers are the most favorable in terms of the permeate flux (Radu et al., 2010); this finding match our results obtained for the biofouled FO systems, in which the submerged spacers generate a better performance than spacers in cavity configuration.

Regarding the local effect of biofilm on CP, Radu et al. (2010) conclude that the thickness of biofilm proportionally correlates with the amount of solute that accumulates at the vicinity of the RO membrane. This is also consistent with the results obtained with the present model for FO.

Spacers and biofilm appear to have an important role in both, RO and FO systems.

5.3. Further model development and use

The model used in the different studies can be adapted with other parameters to predict the impact of biofilm on FO systems under different conditions.

Although the developed two dimensional model gives an insight of the potential problems that biofilm might have on the performance of FO systems, it completely neglects the changes in
flow velocity, biomass, and solute concentration in the z-direction. This might affect the results obtained for the performance indicators analyzed (Radu, et al. 2010). Thus, for a better comparison with experimental measurements, an increase in knowledge is needed, which translates into the development of more complex geometries (three dimensional models). This will also yield a better understanding and prediction of the impact of biofilm on FO systems.

Additionally, studies should consider time-dependent processes such as biomass attachment, detachment, biofilm growth, and substrate uptake by the biomass. These additions will enable a complete and more realistic study of the phenomena occurring in over time, in view of the achievement of better performing FO systems.
6. CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

Based on the developed two dimensional numerical model to assess the impact of (i) spacers, (ii) biofilm, (iii) biofilm membrane surface coverage, and (iv) spacers and biofilm combined; the following conclusions can be drawn:

- The water flux as an indicator of FO performance was improved in the presence of spacer.
- The amount of biofilm relates proportionally to the total water flux decline across the membrane.
- Higher membrane surface coverage by biofilm is related with higher total water flux decline across the membrane.
- The membrane surface coverage by biofilm has a more important impact on the total water flux than the total biofilm amount.
- For clean FO systems, the cavity spacers yield a better performance, by increasing the total water flux. Whereas for biofouled FO systems, spacer in submerged configuration produce higher water flux.
- ICP plays an important role on the system performance.
- The model might help to optimize membrane device construction and operation in less time and lower cost.
6.2. Recommendations

- Evaluate the limitations of the model using different parameters (e.g.: spacer and membrane thickness, biofilm amount, channel height, feed and draw solute concentration, etc.) and operational conditions (e.g.: comparison between counter flow and parallel flow, inlet flow velocities, etc.).

- Development of two dimensional model considering time dependent processes such as:
  - Biomass growth and substrate uptake
  - Biomass attachment and detachment

- Development of three dimensional model of FO systems which includes hydrodynamics, spacers, and biofilm.

- Development of three dimensional model considering time dependent processes such as:
  - Biomass growth and substrate uptake
  - Biomass attachment and detachment
7. BIBLIOGRAPHY


