Seawater-induced Biofouling in Direct Contact Membrane Distillation

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ABSTRACT

Membrane distillation (MD) is a promising desalination technology which achieves high salt rejection at low energy expenses as compared to conventional desalination processes. However, just like any other membrane separation process, the MD membrane is susceptible to biofouling which is one of the critical problems in membrane-based systems. In this study, we investigated the effects of spacer design and feed temperature on the biofilm formation and proliferation in a direct contact membrane distillation (DCMD) process used for desalination of the Red Sea water. Two types of spacers (standard and 1-Hole) were tested for their efficiency in biofouling mitigation at three different feed water temperatures (47 °C, 55 °C and 65 °C). Our results showed that 1-hole spacer was more efficient in reducing biofouling at 47 °C as compared to standard spacer. The corresponded permeate fluxes declined by 73.2% and 79.6% after 5 days of DCMD process for 1-hole and standard spacers, respectively. As opposite, the standard spacer over-performed the 1-hole spacer at higher feed water temperatures. The corresponded permeate fluxes declined by 65.7%, and 75.1% and 75.2% and 84.1% after 5 days of DCMD process for standard and 1-hole spacers at 55 °C and 65 °C, respectively. The Optical Coherence Tomography revealed significant changes of biofilm morphology with increasing feed water temperature for both types of spacers. While thicker and more porous biofilm structures were formed on the surface of MD membrane at 47 °C and 55 °C, thinner non-porous layer prevailed on the membrane surface at a feed water temperature of 65 °C. This observation was supported by direct enumeration of bacterial cells inside the biofilm by flow cytometry which revealed a significant decrease in the total number of cells when the feed water temperature was increased from 55 °C to 65 °C. Moreover, this process was accompanied by the
permeate flux decline and increase of coolant water conductivity regardless of the spacer type. The results of our study showed high rejection of dissolved organic carbon (> 97%) and absence of bacterial contamination of permeate water which is important due to the use of microporous polymeric membrane with 0.45 μm pore sizes.
To my parents,
For all their love and support
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1 Chapter 1
1.1 Introduction

On a global scale, the demand for freshwater is expected to increase in the coming decades to reach 40% of the total water demand by 2030 [1]. On the other hand, the increase in the world population is growing from 6.8 to reach 8.9 billion by 2050 [2]. The increase in the global population, economic, climate change and the rapid industrialization all are accelerating many regions to be in high stress on water resources [1]. Serious strategic has been followed to mitigate the growing crisis with the water desalination processes providing auspicious solutions for producing freshwater. According to the International Desalination Association (IDA), up to 150 countries have selected to produce their freshwater by using desalination technologies Error! Not a valid bookmark self-reference.; moreover, the global yielding of the freshwater has reached approximately 90 million m³/day from more than 16,000 desalination plants [3].
Almost 48 percent of the worldwide desalination plants are located in the Middle East and North Africa region; with 15.5% of the desalination capacity being possessed by Saudi Arabia, and 10.1% by the United Arab Emirates [4]. In Saudi Arabia, over 82% of water supply is consuming by the agriculture sector (20 billion m$^3$yr$^{-1}$), which is the major water consumption in this area [5]. Therefore, according to Gulf Cooperation Council (GCC) report [6], the growing need for water encourages investments in huge desalination technologies with sustainable solutions. In the 1950s and 1960s, seawater desalination plants were initially constructed to produce freshwater by separation seawater that contained 35 000 ppm of NaCl into deionized water and brine. The produced freshwater should not be exceeded 280 ppm of NaCl [7-9]. The desalination technology has classified into two major sections which are

**Figure 1:** Worldwide distribution of desalination plants (Edward Jones et al. 2019).
thermal or membrane-based technologies [9]. In the early 1970s, nations which experienced draught, chose to produce freshwater by thermal desalination technologies such as Multistage Flash (MSF), which require a huge amount of energy and complex maintenance [10]. In contrast, membrane-based technologies were grown rapidly over the last few decades Figure 2, such as reverse osmosis (RO) which is the most dominant in the global market [11]. Other promising desalination technologies, such as membrane distillation (MD) and humidification-dehumidification (HDH) are thermal-energy-driven technologies that exceed RO technology by producing higher quality product water, increased fouling resistance and reduced energy consumption if coupled with renewable energy sources [12]. In general, Membrane-based technology is a promising and more effective for desalination applications. Membrane-based technology attracted more researchers to improve and enhance the technology as shown in Figure 3. The characteristic of the membrane is playing a big role in its permeability and rejection of salts which uses the advantage of the nanotechnology [13]. One of the high efficient membrane in salt rejection was membrane distillation (MD), which uses thermal driven force to heat water for the evaporation process at low temperature and hydrostatic pressure, which then condensation occurs to produce distilled water. The hydrophobicity
of the MD nanofibrous membrane allowing only vapor molecules to pass through it from the hot side to coolant side which has lower vapor pressure than the feed side [13].

1.2 Study objectives and layout

The aim of this study was to systematically investigate the biofouling attachment and proliferation during DCMD process with high salinity Red Sea water. The specific objectives of this study were as follows: (1) to investigate the effect of the feed channel spacer type (cylindrical with no holes/standard and cylindrical with a hole at the filament intersection/1-Hole) on permeate flux and biofouling development; (2) to investigate the effect of the feed water temperature on permeate flux and biofouling development; and (3) to investigate the effect of biofouling on permeate water quality.

The DCMD process was operated at three different feed water temperatures of 47 °C, 55 °C and 65 °C. The Optical Coherence Tomography (OCT) was employed to evaluate the evolution of biofilm’s morphology during five days of continues DCMD process. The bacterial cells in biofilm and feed/permeate waters were quantified and identified (live/dead) by using flow cytometry (FCM) analysis. The Confocal Laser Scanning Microscopy (CLSM) was used in this study to investigate the bacterial distribution on the MD membrane surface. The permeate quality was evaluated in terms of dissolved organic carbon (DOC) and conductivity.

The structure of the thesis is as follows. Chapters 1 and 2 provide a brief overview of desalination technology; membrane-based filtration; MD technology and module configurations; membrane fouling (biofouling) mitigation techniques; and description of
Chapter 2

2.1 Literature review

2.1.1 Membrane distillation technology

Membrane Distillation (MD) is a highly promising technology to separate high salt concentrated water by thermally-driven force, which allows only water vapor to pass through the microporous membrane. MD separation occurs by passing water vapor through the permeable hydrophobic membrane as a result of vapor pressure difference that is enhanced by the differences of temperatures between two membrane sides as shown in Figure 4 [12]. In other terms, the non-volatile compounds are not passing through the MD pores and will retain to the feed tank while the volatile compounds are allowed to pass through.

Figure 4: Membrane distillation (MD) process concept. (Eykens et al. 2017)
the pores. This is happening due to the hydrophobicity of MD membrane which prevents any liquid phase from entering the membrane pores [14]. Theoretically, a 100% separation may occur [15]. Membrane distillation system has many advantages in comparison to the conventional thermal processes due to its ability to operate at low feed water temperatures with no need to reach boiling point [12]. Therefore, the MD process is a cost-effective and energy-efficient especially when it is coupled with the solar [16], geothermal [17] or nuclear [18] sources of energy (Figure 5).

Moreover, the MD process has lower hydrostatic pressure than the pressure-driven membrane processes such as reverse osmosis (RO). The hydrophobicity of membrane minimizes the occurrence of corrosion due to the high rejection factor (99 to 100%) for non-volatile compounds such as colloids and salts, as well as macromolecules, inorganic ions, and heavy metals [15]. Additionally, MD membrane exposed less fouling than RO and NF as a result of the hydrophobic membrane and large pores size [13]. In order to achieve a high performance of MD, the focus on membrane structure should be an
important factor. MD possess high porosities and large pores for vapor molecules transportation, and a hydrophobic membrane which limits the formation of fouling and wetting [15]. The permeate flux of MD is affected by temperature polarization and mass transfer resistance of membrane, where the existence of high porosity and large pore sizes can mitigate the effect on the flux decline [15]. MD process involves in industrial water desalination (such as food industry), wastewater treatment, [19] as well as in radioactive waste treatment where the treated water could be safely released to the environment [13, 20].

2.1.2 MD configurations

In accordance with the methods to produce the water in the permeate side as a result of the vapor pressure gradient across the membrane, several MD configurations have been proposed. MD process classified into four main configurations, including Direct Contact Membrane Distillation (DCMD), Air Gap Membrane Distillation (AGMD), Sweeping Gas Membrane Distillation (SGMD) and Vacuum Membrane Distillation (VMD). In all configurations, the feed solution always remains in direct contact with the membrane. However, varies cell design is to improve the permeate flux and energy efficiency by changing the manner of vapor pressure differences across the MD membrane as shown in the figures below.

2.1.2.1 DCMD

DCMD is classified as the simplest MD configuration, in which the cold and hot solutions
are in direct contact with the membrane as shown in Figure 6, the water vapor is transferred from the hot feed side (Region 1) to the cold permeate side (Region 3), through the hydrophobic membrane (Region 2) [21]. The temperature difference in DCMD module induces the vapor pressure gradient which is the main driving force for volatile molecules to evaporate from the hot feed side across the membrane followed by the condensation process at the cold liquid interface [22]. The DCMD has received more attention than other configurations in the research applications due to its simplicity and high permeate fluxes [23] achieved without the use of external condenser [24]. That makes DCMD process setup suitable for seawater and brackish water desalination [25] as well as in pharmaceutical, industrial chemical waste [26] and highly saline radioactive wastewater [27] managements. The challenge in DCMD is the high heat losses since the only barrier between the hot feed and the permeate side is the MD membrane itself [25].
Figure 6: Schematic of the DCMD configuration. (SO Olatunji et al. 2018)

2.1.2.2 AGMD
AGMD configuration has a stagnant air gap channel between the cold permeate side of the membrane and condensation surface as shown in Figure 7. The evaporation process is occurred in the feed region, the vapor molecules pass through the hydrophobic membrane pores to the air gap, and the condensation occurs on a surface of a cooling plate which separates air gap from the coolant side of AGMD module [28]. The permeate is then collected at the bottom part of the module [29]. The existence of air gap is helping to reduce the heat loss which occurred by conduction, thus it will improve heat efficiency [30, 31]. Accordingly, AGMD configuration is more energy efficient in comparison to other MD configurations, which promoted its application in not only water desalination applications but also for the removal of specific volatile organic compounds (VOCs) [32, 33].

![Figure 7: Schematic of the AGMD configuration.](SO Olatunji et al. 2018)
SGMD configuration involves cold gas stream that sweeps water vapor from the permeate side to the outside of the module where condensation take place (Figure 8). Therefore, SGMD needs to have an external condenser to condense the vapor outside the module [34]. The advantage of using SGMD is its ability to produce a higher vapor flux than that of AGMD as a result of reducing the mass transfer resistance. Moreover, SGMD has higher evaporation productivity than DCMD due to decreased conductive heat losses. However, the practical application of this configuration is limited due to the high costs of sweeping gas and external condenser [35].

![Schematic of the SGMD configuration](image)

**Figure 8:** Schematic of the SGMD configuration. (SO Olatunji et al. 2018)

### 2.1.2.4 VMD
The VMD configuration (Figure 9) involves application of vacuum on the permeate side of the membrane to remove the water vapor from the module. The applied vacuum pressure has to be lower than the saturation pressure of volatile molecules [22]. The VMD condensation occurs outside the module which requires an external condenser to collect the permeate flux. The main advantage of the VMD configuration is lower conductive heat losses due to insulation properties of vacuum. Furthermore, the diffusion of evaporated molecules through the membrane pores is favorable, thereby reducing the mass transfer resistance. In other terms, the heat transfer resistance by conduction inside membrane pores and permeate side can be ignored in the VMD module [25].

Figure 9: Schematic of the VMD configuration. (SO Olatunji et al. 2018)
2.1.3 Membrane Fouling

In general, fouling is a major problem in the membrane-based process which is defined as the accumulation of unwanted materials on the surface of the membrane or inside the pores (Figure 10) as well as on the feed spacer. Fouling causes a decline in the permeate flux and salts/organics removal efficiency that reduces the overall membrane performance [36]. In pressure-driven membrane processes such as RO, NF and etc., the damage caused by fouling is very high which is affecting the desalination process [37]. The Results showed that forward osmosis (FO) has the highest resistance against scaling fouling, on the other hand, MD process showed a better resistance of organic fouling than in FO and RO [38]. Although, only a few studies have been done in MD fouling which makes the phenomena still poorly understood [39] [40].

In 2008, Gryta et al. [39] reported a study in which they investigated the fouling mechanisms using wastewater as feed to observe different foulants such as proteins, brines and bilge water in a DCMD process with polypropylene capillary membranes. Different fouling intensities have been found for different feed waters. Therefore, the formation of fouling layers can be classified on the degree of porosity which affects the permeate flux production. Where the less porous fouling layer formation causes a sufficient increase in the mass transfer resistance as well as exponential decrease in permeate flux. On the other
hand, the formation of more porous layer would result in increased heat resistance, thus decreasing the permeate flux. Moreover, the study observed the effect of the flow velocity on the growth rate of the fouling layer. The higher flow velocity allows CaCO$_3$ crystals to form on the surface of the membrane, while the lower velocity created a thicker fouling layer. In another study, in 2011 Kullab et al. [41], found that the fouling of MD membranes can cause pore clogging which negatively affects the vaporization process and decrease the permeate flux. Moreover, fouling creates pressure drop and temperature polarization that effecting negatively in flux [41].

Several factors are affecting the fouling formation on MD membrane surface. Using the integrated approach as shown in Figure 11: (1) properties of the foulant including molecular size, solubility, concentration, and charge; (2) membrane characteristic such as pore size, porosity, hydrophobicity, charge, roughness and composition; (3) operation conditions including feed and permeate flow rates and temperature; and (4) feed water parameters including pH, ionic strength and presence of organic and inorganic matter [36]. In general, fouling can be divided into three major groups: inorganic scaling fouling, organic fouling and biofouling [42]. Below are details of each type of fouling.

2.1.3.1 Inorganic scaling in MD
Inorganic scaling is a crucial in MD membrane, which is a precipitation of inorganic salts on membrane surface or plugging the pores such as calcium sulfate, calcium carbonate, calcium phosphate, silica and etc. Mainly, the formation caused by changes in the temperature and the evaporation process, thus leading to the formation and development of crystals which result in a flux decline [43, 44]. Kang et al. (2002) [42] studied the characteristics of inorganic and organic fouling on the membrane of an anaerobic bioreactor, the evidence shows a cake layer formation that composed of thick biomass and crystallization of Struvite. Generally, the inorganic scaling fouling can be irremovable due to the cohesive characteristic.

2.1.3.2 Organic Fouling.

Organic fouling is a deposition of organic matters on membrane surface such as humic acid, fulvic acid, proteins, polysaccharides, carboxylic acid, and polyacrylic polymers [45]. At the molecular level, the adsorption of organic matter on the membrane surface is usually hard to clean without using chemicals [36]. A study by Fan, L., et al. [46], has been identified the order of organic materials with respect to their fouling potential. The authors reported that hydrophilic neutrals possessed the highest fouling propensity followed by the hydrophobic acids and transphillic acids. The natural organic matter (NOM) is one of the most abundant organic fouling that causes a flux decline due to predominance of humic substances which are the main component of NOM [47, 48]. The NOM is adsorbed on the membrane surface by a number of mechanisms including hydrophobic/hydrophobic interactions, electrostatic interactions [49]. The NOM adsorption inside the pores results in their partial or complete blockage so that the water vapor could not pass through the
membrane. Moreover, the adsorption of NOM can be on the surface of the membrane would led to a formation of a gel-like layer which is also blocking the pores and creates additional resistance to the flow of vapor [50]. In a different study, Gryta et al. [51] investigated the performance of the MD process using NOM/NaCl solutions as a feed. The authors found a rapid flux decline due to the formation of NOM fouling layer. In general, the results revealed that the dominant components in the fouling layer were proteins and sodium chloride. Moreover, a pretreatment method was examined by heating the concentrated salt solution to reach its boiling point which then result in minimizing the fouling layer. Another component (2 wt% citric acid solution) was used to reduce the fouling deposition and enhance the process performance. To date, several studies have found that fouling by polysaccharides and proteins is more common in the MD process as compared to NOM fouling due to their large molecular weights [52, 53].

2.1.3.3 MD Biofouling

In real desalination process, the feed water comprises different inorganic and organic compounds as well as microorganisms. As a result, such systems are highly susceptible to biological fouling which would be developed on membrane surface with time. Biofouling is an accumulation and growth of biological species on the membrane surface, which aversively affects the efficiency of membrane filtration and reduces its lifetime [54]. Biofilm is composed of multilayers of complex bacterial communities that produce extracellular polymeric substances (EPS) mainly composed of polysaccharides and proteins, which form an immobilizing matrix of the live and dead cells [55, 56]. The EPS is accounted for approximately 50-90% of biofilm’s total organic carbon [57]. The
formation and development of biofilm involve serial stages as shown in *Error! Reference source not found.*. The first stage is the attachment of bacterial cells to the membrane surface, which would already have the conditioning film of organic materials such as proteins, lipids, polysaccharides, NOM, HAs, nucleic acids and aromatic amino acids. The attachment of bacteria become more resistant to the environmental changes when they are embedded in a biological matrix that binds bacteria to each other and to the membrane surface [58]. At the molecular level, the marine microbial systems are communicating to each other through a mechanism called quorum sensing (QS), which diffuses chemical signals through the EPS to allow cell-cell interactions so that they will grow and hold together [59]. The dissolved salts can also be trapped inside the biofouling by the EPS and deposited bacterial cells thereby enhancing concentration polarization. As a result, the rejection of salts is decreased [60]. The formation of biofilm on the membrane surface increases its wettability due to amphiphilic properties of EPS so that the feed solution can enter membrane pores. Pore wetting leads to decline in permeate flux and permeate’s quality and promotes temperature polarization [39]. The hydrophobicity of membrane would also be reduced [61].
Previous study showed that the development of biofouling in the MD process is limited due to the operational temperature from 261 K to 383 K, which is lower or higher than the optimal growth temperature of microorganisms [62]. Moreover, the high salinity level of the feed solution during the operation process is expected to limit the microbial growth and development [62]. Furthermore, the inherit properties of MD process such as its operation without applied pressure and the large pore sizes makes MD membranes less susceptible to biofouling in comparison to other membrane processes like reverse osmosis (RO) or nanofiltration (NF) [63]. Krivorot et al. (2011) [64] investigated the biofouling potential of the DCMD process during seawater desalination with respect to high biological load and temperature. At 40 °C, the results showed a decline in the permeate flux by 34% when the high biological load (1 × 10^8 CFU/ml) were applied over 19 days of operation. After 28 h, the biofilm formation was observed on highly hydrophobic polypropylene (using hollow fiber membranes with fluorosilicone coating). Furthermore, less biofouling was observed when experiment operated at a temperature cycles between 40 °C and 70 °C not only fixed
at one temperature, as compared to an experiment which was conducted at a constant temperature of 40 °C. Furthermore, the effect of fiber positions was also investigated and less biofilm was observed at module’s as comparing to module’s outlet, indicating that the temperature differences between these two positions has a significant impact on module’s performance [64]. In a study done by Katherine et al. (2014) [65] who investigated the formation of initial stages of biofilm during four days for both systems DCMD process and RO system with the seawater as feed solution. The type of membrane used in the MD system was 0.2 μm polytetrafluoroethylene (PTFE) membrane. The results showed that the hydrophobic surface of MD membrane contained less foulants when the hot feed stream was operated at 50.4°C while the cold distilled stream was at 18.1 °C, in comparison to the RO system which showed a formation of a thick biofilm layer when the feed temperature was held constant at 25 °C. Also, the results showed that the MD biofilm contained different colonies with different bacterial species, while RO biofilm layer contained homogeneous colonies. In other words, two different systems (MD and RO) developed different microbial communities regarding the phylogenetic analysis using 16S rDNA sequencing. The most abundant microbial species of the biofilm in the MD system were Burkholderiales, Rhodobacterales, and Flavobacteriales [65]. Recently, (Bolger, 2018) [66] studied the impact of different feed water temperatures on biofilm growth in DCMD process with 0.45 μm hydrophobic Durapore® membranes by using an isolated bacterial model (Anoxybacillus sp.) extracted from the effluent of a wastewater membrane bioreactor (MBR). As seen in Figure 13, less bacterial growth was observed on the membrane surface at 47°C which is below the optimal temperature of Anoxybacillus sp growth. As a result, a 30% permeate flux decline was observed. When the feed temperature
was increased to 55°C (optimum temperature of *Anoxybacillus* sp growth), the enormous growth of *Anoxybacillus* sp. was detected causing 78% of flux decline. Despite the thin biofilm layer observed at 65 °C (corresponded to approximately 32% of the permeate flux decline), the excessive EPS formation was detected. As it is also seen in Figure 13, this layer caused pores wettability due to amphiphilic properties of EPS substances [66].

**Figure 13:** The impact of different feed temperature on the biofilm formation and development in MD process. (Bolger, 2018)

### 2.1.4 Spacers

Membrane is the main component of the MD system, but the application of a spacer is also desirable in a full-scale module due to its ability to increase the fluid mixing and generate turbulence in the flow channel thereby promoting the heat and mass transfer through the membrane and reducing concentration polarization. As such, higher permeate flux can be achieved [67, 68]. However, it has been demonstrated that presence of spacer in a feed channel would enhance the biofouling growth and development. In general, the biofilm is
first developed in the vicinity of the spacer and then the speared and cover the membrane surface [69, 70]. Furthermore, the pressure drop in the module is also increased due to the accumulation of microorganisms [71]. In recent study by S. Kerdi et al. 2018 [72], have designed and evaluated a novel spacer by using 3D-printing technology as shown in Figure 14. The concept of this spacer was based on creating holes along the spacer filament to form micro-jets near the membrane surface in order to reduce the dead zones so that the bacterial attachment is minimized. A range of spacers with different number of holes was manufactured and evaluated. It has been found that 1-hole spacer offered the best performance in terms of permeate flux enhancement and reduced biofilm growth.

Figure 14: Schematic of feed spacer shows (A) 3D-printed of standard spacer (0-Hole) and 1-Hole spacer, as well as CAD design and SEM. (B) spacer dimensions in mm. (S. Kerdi et al. 2018)

3 Chapter 3
3.1 Materials and methods
3.1.1 Membrane characterization
The hydrophobic microporous membrane that was used in all biofouling experiments,
composed of a polytetrafluoroethylene (PTFE) which was the active layer facing the feed side. As well as, a thermoplastic polymer was supporting the MD membrane from the back which facing the permeate side was made of polypropylene (PP). The pore size of the membrane was in the range of 0.77 ± 0.03 μm that measured using a porometer (Porolux 1000, IB-FT GmbH), with a membrane thickness of 20 ± 0.4 μm for PTFE layer and 80 ± 1.6 μm for the PP layer. However, the PTFE layer has more porous which equal to 70 ± 5 % than the support layer (PP) with a percent of 34 ± 2.4 %. In this case, the mass transfer will be high through membrane while heat transfer will be less. The membrane water contact angle was approximately 160 ± 3° using an optical tensiometer (Attension T301, Biolin Scientific) [73].

3.1.2 Bench-scale MD system set-up

All experiments in this study were used a custom-designed flat sheet DCMD configuration made of polymethyl methacrylate, which was a transparent thermoplastic material that allowed us to investigate the biofouling formation and development. The DCMD cross-flow system had an active membrane area of 0.0009 m² (1.5 cm x 6 cm), and the channel height was 3 mm in both sides (feed and coolant). The membrane was sandwiched between two spacers, where the PTFE surface was facing feed side while the PP surface was facing permeate side. In this study, two types of spacers with different filament geometry (1) cylindrical with no holes (standard) and (2) cylindrical with a hole at the filament intersection (1-Hole), both having thickness of 1.85 mm. The existence of spacer increased the fluid mixing in the feed channel by generating more flow turbulence to have high improvement of permeate flux. Besides the DCMD module (Figure 15), the system
consisted of feed and permeate tanks where their solutions’ temperature controlled by Refrigerated/Heating Circulator (JULABO, F25-EH). In order to keep the feed temperature stable, thermal insulation of the connecting tubes was used for minimizing the heat loss. The collected permeate weight was monitored by an electronic weighing balance (Mettler Toledo) and the data were recorded by LabView software for calculating the permeate flux using the following equation:

\[
\text{Vapor Flux (kg/m}^2\text{hr)} = \frac{\text{Difference of the accumulated weight}}{\text{Membrane area} \times \text{Time}}
\]

Furthermore, the flow rate was kept constant by using two digital gear pump system (Cole-Parmer). Also, the conductivity was measured to investigate the salts concentration in the permeate tank using conductivity meter as well as an integrated temperature sensor (Cond 3310, TetraCon® 325, WTW). The membrane performance has been tested at the beginning of each experiment using Red Sea water as a feed source after flashing the water through the supply pipeline. Three different feed temperature was used for each experiment (47°C, 55°C, and 65°C), while keeping the permeate temperature fixed at 20°C. The flow rates of feed and permeate solutions were kept constant at 500 ml/min and 280 ml/min, respectively. Moreover, in order to avoid the dropping of the permeate flux due to the effect of increasing the salinity as a result of water evaporation in the feed solution, for that, 10 L of feed solution was used in each experiment. The duration of each experiment was 5 days.
3.1.3 Biofouling procedure

Figure 15: Composition of the experimental-scale of DCMD system. 1: Feed tank filled with 10L solution, 2: permeate tank, 3: Cross-flow DCMD configuration, 4: Heater, 5: Chiller, 6 & 7: Feed and coolant pumps, 8 & 9: Conductivity meter, 10: Weighing balance, 11: Labview software, 12: Overhead Stirrer.
A synthetic feed solution was used for each experiment to enhance the bacterial growth in
the system and to observe the biofilm layer on the membrane surface in a faster manner.
For each biofouling experiment, a fresh solution was prepared by incubating 2.5 L of
seawater with 10 g of Bacto™ Yeast Extract (Extract of Autolysed yeast cells, Becton
Dickinson and Company) at 30°C for 24 h. Yeast Extract was rich with vitamins, nitrogen,
amino acids and carbohydrate which is the source of energy for heterotrophic bacteria [74].
After that, the incubated solution was added into the feed tank and diluted with 7.5 L of
seawater, to reach the final volume of 10 L of feed solution with an initial bacterial
concentration in a range of (~ 6 x 10⁶ cells mL⁻¹) to (2.2 x 10⁷ cells mL⁻¹). for each set of
experiment. A feed solution was continuously mixed at 330 RPM (IKA Overhead Stirrers,
RW 20 digital) to ensure the uniform feed water composition in the feed tank. After each
DCMD run, the cleaning procedure was conducted by circulating 10% of bleach through
the system for 30 min. Then MD system was rinsed 3 times with the Milli-Q water water
for 15 min to remove any remaining residual foulants. A baseline experiment using
seawater as a control was conducted before each fouling experiment to determine the initial
permeate flux. The integrity of MD membrane was monitored by measuring the
conductivity of the coolant water.

3.1.4 Biofouling characterization:

3.1.4.1 Biofilm development using optical coherence tomography (OCT)
OCT is an optical interferometric technique for characterizing biofouling development in
membrane filtration systems as well as observing membrane wetting without using any
stains for the biofilm. Since 1991, OCT was first developed for medical imaging by Huang
et al. [75] then it has been used for biological proposes with 2D and 3D imaging [76, 77]. In our work, we utilized OCT technique to provide high resolution images of the biofilm by placing the scan lens above the crossflow cell to observe the biofilm thickness every 24 h during the experiment. The imaging was achieved using low-coherence light reflection from biofilm structure. The resulting interference pattern was used to generate OCT scans of the biofilm morphology [78]. The OCT scanning was performed at three fixed locations on the active layer (inlet, middle, and outlet of the feed flow) as shown in Figure 16, in order to observe the growth of biofilm using and the signal was recorded by using the Thorlab software. After that, the average biofilm thickness was taken by measuring the length of biofilm at three sites by using ImageJ software (National Health Institute, US) then calculating the average by using the Excel software (Microsoft).

**Figure 16:** Optical Coherence Tomography (OCT) was performed at three different fixed locations (inlet, middle, outlet) in DCMD module.

* Black arrow represents the scanning location near the spacer filament.

### 3.1.4.2 Bacterial abundance by flow-cytometry (FCM)

Bacterial cell count by flow cytometry (FCM) provides an accurate and fast counting for all bacteria in a water sample by using fluorescent stains. The FCM method characterizes
bacteria using side and forward scatter lights [79]. Bacterial abundance calculations were performed first in the feed solution in order to determine the initial bacterial concentration before running each MD experiment, and at the end of the experiment when the cells were extracted from the membrane’s selective layer and were analyzed by the flow-cytometry. In addition, the permeate samples were also collected every 24 h during the five days of MD process in order to investigate the quality of water. In MD samples, the analysis preparation started by cutting membrane coupon (1 cm × 1 cm) and suspended it in 10 ml of 1X Phosphate Buffer Saline (PBS) then sonicated the sample for 30 min to detach the biofilm from the membrane. The aqueous samples were then stained with SYBR® Green I and propidium iodide (PI). Stains were first diluted with Milli-Q water to reach the final concentration of 100X for SYBR® Green, while the optimal final concentration of PI was 6 μm. The total volume of the sample was 200 μl for each well in the 96-well plate, which consisted of 2 μl of the diluted SYBR® Green I, 2 μl of pi and 196 μl of sample. Then plate was incubated at a room temperature in a dark environment for 15 min. The bacterial count was carried out with the fluorescence activated cell sorting (FACS) using measurements of fluorescein isothiocyanate FITC (excitation at 488 nm) and PI (excitation at 670 nm) to determine the live and dead cells. The analysis were repeated three times.

### 3.1.4.3 Biofilm characterization by confocal laser scanning microscopy (CLSM)

Biofilm identification and characterization were performed using CLSM at the end of each experiment. The fouled membrane was cut into small pieces (1 cm × 1 cm from the middle section of the active layer) for staining of the live and dead cells. Membrane coupons were glued with epoxy glue in a small petri dishes and then washed with 1X PBS before staining to
remove unattached microorganism. All samples were stained with 3.34 mM SYTO® 9 green fluorescent nucleic acid stain (S34854, Molecular Probes, Life Technologies, Thermo Fisher Scientific), and 1.5 M PI (P3566, Molecular Probes, Thermo Fisher Scientific) for 30 mins in the dark according to the manual’s instruction. After that, the membrane coupons were washed 3 times for 5 mins each with 1X PBS to remove excessive unreacted stain.

Table 1 Dyes characteristic for CLSM analysis

<table>
<thead>
<tr>
<th>Dye</th>
<th>Excitation/Emission</th>
<th>Target</th>
<th>Final Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>SYTO® 9</td>
<td>488/500 nm</td>
<td>Live and dead bacteria (green color)</td>
<td>6 μm</td>
</tr>
<tr>
<td>Propidium iodide</td>
<td>535/617 nm</td>
<td>Dead bacteria (red color)</td>
<td>30 μm</td>
</tr>
</tbody>
</table>

Finally, the stained coupons were ready for imaging using CLSM (LSM710 upright confocal microscope, Carl Zeiss, Germany), with 40× water-immersion objective lens that allowed a clearer images for biofilm. CLSM provides images of high resolution 2D and 3D structures by using ZEN software. Which obtained by Z stack option to scan the images vertically with a thickness of 20 - 40 μm to characterize the distribution of live and dead cells within the biofilm. Finally, the images were analyzed and edited by Imaris software to prove the visualization of the 3D structure.

3.1.5 Dissolved organic carbon (DOC)

Dissolved organic carbon (DOC) analysis was applied to quantify all organic carbon after DCMD filtration process in order to investigate the water quality. In which the permeate
samples were collected every 24 h during the five days of running the biofouling experiment. After that, the collected samples were placed in 20 mL glass vials, the original feed sample was diluted with 15 ml of MQ water because of its high turbidity and organic content. The prepared samples were analyzed using TOC analyzer (TOC-LCPN, Shimadzu Co.). The process started with the combustion furnace (heating up to 680 °C), which converting all the organic compounds in a complex sample to carbon dioxide that detecting by non-dispersive infra-red (NDIR). Then the percentage of rejection was calculated using TOC concentration through the following equation:

\[ R = \left(1 - \frac{C_p}{C_f}\right) \times 100\% \]

Where, (R) represents the rejection, (C_p) DOC concentration of the permeate sample, and (C_f) TOC concentration of the feed sample.
4 Chapter 4

4.1 Results and discussion

4.1.1 The effect of biofouling on permeate flux under different temperatures

The effect of biofilm on vapor flux was investigated for three different feed temperatures at 47 °C, 55 °C and 65 °C, with the coolant temperature being constant at 20 °C for all cases. We used a constant feed flow rate of 500 mL/min as well as a coolant flow rate of 280 mL/min. For each biofouling experiment, the feed solution consisted of 10 L of Red Sea water with 10 g of Bacto™ Yeast Extract as a nutrient source for accelerating the aquatic bacterial growth in a short time. The initial bacterial concentration of the feed solution depended on the feed temperature which ranged between (∼ 6 x 10⁶ to 2.2 x 10⁷ cells mL⁻¹). We observed an increase in permeate vapor flux with increasing feed temperature. The reason for this increase was an increase in vapor pressure so the mass transfer increases accordingly. The baseline tests were conducted before each biofouling experiment to check the membrane’s integrity. A baseline test was run by using 10 L of seawater at 47°C for three days. The initial permeate flux of MD membrane for the baseline test was 24.02 kg/m²h. While the baseline test for 55°C and 65°C were run only
for an hour with an initial permeate flux of 41.5 kg/m²h and 65.43 kg/m²h, respectively.

As shown in

**Figure 17.** A gradual flux decline was observed in experiments at 47°C with both standard and 1-Hole spacers. The initial permeate fluxes were 24.02 kg/m²h and 19.3 kg/m²h using standard and 1-Hole spacers, respectively, and these values decreased by 79.6% and 73.2% at the end of day 5, respectively. At a feed temperature of 55°C (
Figure 18), the initial permeate fluxes were 41.8 kg/m²h and 31.6 kg/m²h using standard and 1-Hole spacers, respectively, and these values decreased by 65.67% and 75.1% at the end of day 5, respectively. At higher feed temperature of 65°C (Figure 19), the initial permeate fluxes were 63.4 kg/m²h and 52.5 kg/m²h using standard and 1-Hole spacers, respectively, and these values decreased by 75.16% and 84.14% at the end of day 5, respectively. Our results indicated a significant impact of the feed temperature on biofilm formation and permeate water flux. Previous investigations pointed out the impact of biofouling on MD membrane refers to the changing in the temperature of the feed and coolant solutions. In addition, concentration polarization near the membrane surface which has a significant effect on mass transfer and membrane biofouling also results in permeate flux decline [80]. Furthermore, the pore blockage caused by biofouling formation, increased membrane’s resistance so less vapor will travel across the membrane. In this study, we investigated the effect of biofilm formation on permeate flux under different temperatures. Which may be referred to the initial membrane wetting due to the
high attachment of inorganic and organic fouling [66, 81]. Although thicker biofilm layer was formed at 47°C and 55°C (Figure 17 and
Figure 18) as compared to that at 65°C, larger permeate flux decline was observed at 65°C (Figure 19) due to the formation of a compacted layer on the MD surface that minimized the air voids within the biofilm thus making it more uniform. In addition, the driving force was higher at 65°C, in comparison to 47°C and 55°C thereby enhancing permeate flux and, as a consequence, biofilm growth. In a previous study, Kerdi et al. [72] investigated the performance of standard and 1-Hole spacer to improve the permeate flux during ultrafiltration of Red Sea water. The authors found that 1-Hole spacer had better performance than other spacers in providing high permeate flux and minimizing the biofouling [72]. Although significant differences were observed in our study between the standard and 1-Hole spacers regardless of the applied feed water temperature, the standard spacer over-performed 1-Hole spacer at 55°C and 65°C while 1-hole spacer produced better fluxes at 47°C.
Figure 17: Permeate water flux at 47°C of the feed solution temperature in the biofouling experiment during 5 days.
**Figure 18**: Permeate water flux at 55°C of the feed solution temperature in the biofouling experiment during 5 days.

**Figure 19**: Permeate water flux at 65°C of the feed solution temperature in the biofouling experiment during 5 days.
4.1.2 Change in biofilm morphology using OCT

Biofouling development has been investigated by the Optical Coherence Tomography (OCT) technique every 24 h during the entire MD operation time and the effect of the feed temperature and feed spacer type were investigated. The two-dimensional OCT scans were performed at three different fixed locations on membrane surface (inlet, middle, and outlet) 

Figure 20.

As seen in Figures 21-23, there is a direct correlation between the biofilm morphology and permeate flux decline. The general trend of biofilm development was the following. After 24 h of MD, a formation of randomly distributed biofilm was detected. After 48h, the membrane surface was covered with a thin biofilm layer. The biofilm thickness was increasing with the MD time reaching up to ∼130 μm at the end of day 5. Consistently with other studies [82], more biofilm was grown near the spacer filaments in comparison to biofilm grown at the center of the membrane. We then compared the biofilm development during the MD process with respect to a spacer type. In Figure 21, shows the OCT scans taken in the middle of the active membrane at 47°C with standard (A) and 1-Hole (B) spacers. As seen in Figure 21, at the end of day 5, a thicker biofilm (∼111μm) was formed in case of standard
spacer as compared to that of 1-Hole spacer (∼70 μm). The observed results are well-correlated with the trends of permeate flux decline (Figure 17) in which higher permeate flux decline was observed in case of standard spacer (79.6%) comparing to that of 1-Hole spacer (73.2%).
On the other hand, the growth of biofilm at 55°C and 65°C was higher during the MD process with 1-Hole spacer than with the standard spacer. As seen in Figure 22 Figure 23, more biofilm was grown near the spacer filament after 5 days of MD process in case of 1-Hole spacer (thicknesses of ∼130 μm and to ∼52 μm at 55°C and 65°C, respectively). On the contrarily, the biofilm thicknesses in case of standard spacer were ∼53 μm and ∼16 μm at
55°C and 65°C, respectively. When comparing the temperature effect on biofilm growth, it is clearly seen that the resulted biofilm structure at 55°C was more loose and porous as compared to that developed after day 5 at 65°C. In contrast, the structure of biofilm which grown on the membrane surface at 65°C was uniform and compacted resulting in more flux decline (84.14% and 75.16% for the 1-Hole and standard spacers, respectively).

![Figure 23](image)

**Figure 23:** Biofilm development by OCT at 65°C during 5 days of the operation time, where (A) represent the biofouling experiment using Standard spacer, and (B) represent the 1-Hole spacer. The fixed scanning location was taken at the middle of the module, near the spacer filament as shown in Figure 16.

It is known that microorganism can tolerate the extreme thermal conditions by producing a higher amount of EPS [83]. As such, more EPS is expected to be produced when the feed
water temperature was increased to 65°C resulting in formation of denser biofilm structures. The examination of the biofilm growth patterns in different feed channel locations revealed that biofilms grown in the middle and outlet parts were thicker comparing to that grown at the channel’s inlet. Generally, the temperature of the feed water decreases as it moves along the feed channel due to temperature polarization which is caused by latent/conductive heat losses. Moreover, it has been suggested that in the MD module, bacteria tend to attach to colder membrane surfaces to reduce the heat stress [84]. As such, it is expected that middle and outlet parts of the feed channel would attract more bacteria from the feed water so that thicker biofilms would also be developed in those locations. In terms of minimizing the biofouling growth, 1-Hole spacer produced the best performance at 47°C, while at 55°C and 65°C it performance in reducing microorganisms attachment was less efficient as comparing to 1-Hole spacer.

4.1.3 Microbiology analysis (FCM, CLSM):

4.1.3.1 Flow Cytometry (FCM)

We have also conducted flow cytometry measurements (FCM) to evaluate the effect of feed water temperature and spacer type on bacterial profile of the feed and permeate water and biofouling layer after five days of MD process at three different feed temperatures (47 °C, 55 °C and 65 °C) and in presence of two different spacer types (standard and 1-Hole spacer).

**Figure 24:** An example of a FCM bacterial density plot illustrating the gating strategy. Where the green color represents the live cells and red color represents the dead cells.
spacers). This technique was used to determine the live cells by using SYBR green and dead cells by using PI. FCM data can be calculating by fixing the gate to exclude the background noise, and to count the live/dead cells as shown in Figure 24. The feed samples were collected after heating the feed solution to a respective temperature to determine the initial bacterial concentration in each MD run to make sure that initial filtration conditions were kept the same for each MD run. As seen in Error! Reference source not found., an increase in the bacterial growth on MD membrane was observed with the increase in the feed water temperature. Moreover, the bacterial count on the membrane surface was higher at 47°C (in case 1-Hole spacer) and 55°C as compared to that at 65°C for both types of spacers. The bacterial count at 47°C in case standard spacer was not conclusive due to technical problems and needs to be repeated. Interestingly, as also seen in Error! Reference source not found., the amount of dead cells in the biofouling layer was almost one order of magnitude less as compared to live cells regardless of temperature and spacer type even after five days of MD process. Our findings were agreed with a previous study [66] in which the higher bacterial abundance on MD membrane samples were at 55°C comparing to 65°C. Overall, FCM results revealed the effect of feed water temperature on the number of bacteria present on the membrane surface. Moreover, a good correlation between the thickness of the biofouling layer and the number of bacteria was observed for each spacer type at 55°C and 65°C. Thus, for the standard spacer, the thickness of the biofouling layer decreased from 53 μm to 16 μm and the total number of bacteria decreased from $1.52 \times 10^7$ cells/cm² to $7.05 \times 10^6$ cells/cm². In case of 1-Hole spacer, the thickness of the biofouling layer decreased from 130 μm to 52 μm and the total number of bacteria decreased from $1.18 \times 10^7$ cells/cm² to $9.6 \times 10^6$ cells/cm².
Confocal laser scanning microscopy (CLSM) analysis was used in this study to visualize the biofilm grown on the membrane surface at different feed temperatures after five days of each MD experiment. In order to identify the live and dead bacteria in the biofilm, the SYTO 9 green fluorescent nucleic acid stain and the red fluorescent nucleic acid stain (PI) were used to stain the membrane surfaces. The 3D images of the biofilm were obtained by the Z-stacks (vertical biofilm images). Figure 26 Figure 27, show the 3D images from top and side views of biofilm developed on the membrane surface during the DCMD process with 1-Hole spacer at 55°C and 65°C, respectively. Consistently with the OCT observations, the biofilm thickness was higher at 55°C (average thickness ∼ 40μm) as compared to that at 65°C (average thickness ∼15 μm). While estimation of biofilm

Figure 25: Bacterial abundance on DCMD membrane surface by flow cytometry at different feed temperatures which shows live and dead cells. *Error bars represent standard deviation of three repeats.

4.1.3.2 Confocal laser scanning microscopy (CLSM)

Confocal laser scanning microscopy (CLSM) analysis was used in this study to visualize the biofilm grown on the membrane surface at different feed temperatures after five days of each MD experiment. In order to identify the live and dead bacteria in the biofilm, the SYTO 9 green fluorescent nucleic acid stain and the red fluorescent nucleic acid stain (PI) were used to stain the membrane surfaces. The 3D images of the biofilm were obtained by the Z-stacks (vertical biofilm images). Figure 26 Figure 27, show the 3D images from top and side views of biofilm developed on the membrane surface during the DCMD process with 1-Hole spacer at 55°C and 65°C, respectively. Consistently with the OCT observations, the biofilm thickness was higher at 55°C (average thickness ∼ 40μm) as compared to that at 65°C (average thickness ∼15 μm). While estimation of biofilm
thickness revealed positive correlation with the OCT imaging, no particular trend regarding the spatial distribution of live/dead cells within the biofilm structure was found. As seen in Figure 26 which represents the CLSM images taken at two different random membrane locations (A and B), while live cells (green color) dominated in image (B), more dead cells (red color) was observed in image (A).

Figure 26: CLSM 3-D images (A and B) of biofilm development on DCMD membrane surface at 55°C of the feed temperature after 5 days of running the biofouling experiment. Live cells are stained with green and dead cells are stained red.
4.1.4 Permeate Water Quality Analysis

4.1.4.1 Conductivity

The conductivity of the permeate water was measured daily during five days of each set of biofouling experiment. A digital conductivity meter (Cond 3310, TetraCon® 325, WTW) was used in this study. As mentioned above, the baseline experiment was conducted initially to check the integrity of each MD membrane. The conductivity of the permeate samples in the baseline experiment was stable in the range of 10.8-12.3 μs/cm during three days of experiment. For the biofouling experiments (Figure 28), a significant increase in the conductivity of the permeate water was detected during the five days of MD experiments regardless of the applied feed water temperature and spacer type. The increasing of the conductivity was an indication of biofilm growth and development. However, the extent of such increase was different for different feed water temperatures.
As shown in Figure 28 (A), at 47°C the permeate conductivity increased from 13 μs/cm at a time = 0 to 130.7 μs/cm at the end of day 5 and from 14 μs/cm at a time = 0 to 92.8 μs/cm at the end of the filtration time for standard and 1-Hole spacers, respectively. A similar trend was observed at 55°C by using a standard spacer (Figure 28, B). In this case, the permeate conductivity increased from 12.3 μs/cm at a time = 0 to 129.3 μs/cm at the end of day 5 and from 13.2 μs/cm at a time = 0 to 97.5 μs/cm at the end of the filtration time for standard and 1-Hole spacers, respectively. Comparatively, as shown in (C), at 65°C, the conductivity of permeate side increased from 15 69.4 to 69.4 μs/cm, and from 12.7 μs/cm to 53.2 μs/cm for standard and 1-Hole spacers. The observed difference is likely due to increased density of the biofouling layer at 65°C which may offer an additional rejection to the salts and low molecular weight organic compounds which comprised conductivity of feed water.

**Figure 28**: Water quality of permeate samples using conductivity meter during the five days of the DCMD operation process.
The observed results are well-correlated with the results of previous studies, in which the formed biofouling layer produced greater conductivity increase as compared to other types of membrane fouling (e.g., scaling) [85, 86]. The biofouling of membrane surface will lead to the accumulation of feed water constituents at the membrane surface and eventual increase in concentration polarization and organic fouling/wetting. As such, the hydrophobicity of membrane’s selective layer will decrease thereby allowing the salts to enter the membrane pores. As such, the conductivity of permeate will increase.

4.1.4.2 DOC

Dissolved organic carbon (DOC) was measured in permeate samples to determine the separation efficiency of the organics removal during MD process and effect of biofouling formation on this process. Error! Reference source not found. shows the changes in DOC rejection at different feed water temperatures and spacer types during five days of MD operations. As seen in Error! Reference source not found., a significant DOC removal was observed of above 97% regardless of feed water temperature and spacer type. Moreover, no significant changes in DOC rejection was observed with the increase in MD operating time suggesting a negligible effect of biofouling formation on DOC removal rate.
Moreover, we also utilized the flow cytometry analysis to investigate if the accumulation of bacteria in the biofouling layer which was formed on the membrane surface promoted bacterial passage to the permeate side. In order to do so, we quantified the number of bacteria in permeate samples every 24 h in each MD biofouling experiment. As seen in Error! Reference source not found., no significant changes in bacterial population of permeate sample at 20°C (the temperature of coolant water) was observed regardless of the spacer type and feed water temperature indicating that the membrane remained impenetrable for the bacterial cells which accumulated at the feed side. Our earlier measurements revealed that the average pore size of the membrane used in this study was 0.5 μm. Given that majority of bacteria are rods with compatible diameters, the membrane surface presents a physical barrier which prevents bacterial passage to the permeate water. As such, it can be stated that biofouling did not deteriorate the permeate water quality with respect to...
5 Chapter 5

5.1 Conclusions

In this study, the impact of a type of feed channel spacer on biofouling development was investigated in DCMD process by using Red Sea water. The experiments have shown that the permeate flux and overall DCMD efficiency can be significantly reduced due to the formation of biofouling on/in the hydrophobic MD membrane. The main conclusions from this study are as follows:

- There is a significant effect of the feed channel spacer geometry on the development of biofouling on the surface of hydrophobic PTFE membrane. We observed a transition in spacer performance with respect to increasing feed water temperature. Thus, while 1-hole spacer was more efficient in reducing biofouling at 47 °C (permeate flux declines of 73.2% and 79.6% after 5 days of DCMD process, respectively), standard spacer over-performed at higher feed water temperatures (65.7% and 75.1% and 75.2% and 84.1% after 5 days of DCMD process at 55 °C and 65 °C, respectively).

- The feed water temperature exerted a significant effect on biofouling layer morphology. While thicker and more porous structures were formed on the surface...
of MD membrane at 47 °C and 55 °C, thinner non-porous layer prevailed on the membrane surface at a feed water temperature of 65 °C. This was well correlated with the number of bacterial cells inside the biofouling structure which significantly decreased when the feed water temperature was increased to 65 °C for both spacer types.

- The extent of permeate flux decline at 55 °C and 65 °C was reversely proportional to the thickness of the biofouling layer for both types of spacers (i.e. less flux decline was observed for thicker biofouling layers). This implies a combined effect of the feed water temperature and biofouling layer composition on permeate flux in the DCMD process.

- The analysis of spatial distribution of biofilm inside the feed channel revealed that thicker biofilms were developed in the middle and feed outlet locations as compared to the inlet position.

- The live bacteria dominated dead bacteria in the biofouling layer regardless of spacer type and feed water temperature.

- The rejection of conductivity-causing compounds was negatively affected by biofouling development as indicated by the increase of coolant water conductivity regardless of the spacer type and feed water temperature.

- The results of this study have shown that the DOC rejection was not affected by the biofouling formation and was steadily high during the course of DCMD (>97%).
5.2 Recommendations for future work

- It is recommended to conduct DCMD process without feed spacer to obtain better insight into fundamentals which govern biofouling processes on the surface of MD membrane and to determine key factors which if the observed fouling trends were spacer-induced.

- To quantify the extracellular polymeric substances (EPS) present in the biofouling layer at different feed water temperatures to obtain better understanding of the biofouling layer morphology and its effect on permeate flux and quality.

- To investigate the effect of MD membrane pore size on biofouling development and microbiological safety of permeate water.

- To investigate the effect of biofouling on MD membrane wetting.

- To investigate the effect of biofouling on rejection of low molecular weight (MW) organic feed water contaminants (e.g., compounds with the MWs below 300-400 kDa).

- To investigate the effect of feed water matrix and salinity (e.g., brines from different desalination processes RO, MSF, MED) on biofilm growth and development.

- To investigate the effect of the feed flow rate on biofouling development during DCMD process.
References


APPENDIX

B)

C)
Figure 31: Normalized permeate flux (A) at 47°C (B) 55°C (C) 65°C of the feed solution temperature in the biofouling experiment during 5 days.
Figure 32: Permeate water flux using different types of spacer (A) Standard spacer, (B) 1-Hole spacer. Where blue color represents biofouling experiment at 47°C of the feed solution temperature during 5 days. Red & black colors represent feed temperature at 55°C & 65°C, respectively.