REMOVAL OF NATURAL ORGANIC MATTER AND HEAVY METAL USING CHARGED ULTRAFILTRATION MEMBRANES

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Abstract

Membrane processes are recognized to be progressively used in drinking water treatment to meet more stringent water quality regulations. Ultrafiltration (UF) has been widely utilized for advanced water treatment to remove colloidal particles, heavy metals, and some of natural organic matter (NOM); however, it cannot effectively remove NOM and heavy metals due to large pore sizes.

Additionally, previous studies have already indicated that modified negatively charged regenerated cellulose (CRC) membranes with larger spacer arm lengths have better removal of NOM, while reducing flux decline during filtration process. Also, in aqueous solution, heavy metal typically complexes with NOM when they are coexisted, which provides the opportunity of using charged UF membranes for simultaneous removal of NOM and heavy metal.

Hence, the negatively charged UF membranes with different spacer arm lengths for simultaneous removal of NOM and heavy metal were investigated in this project. The goal was to explore the possibility of using charged UF membrane for the effective simultaneous removal of NOM and heavy metal. The commercial uncharged regenerated cellulose membranes (CRC) were modified to obtain a series of negatively charged membranes with different spacer arm lengths. Compared with the essentially unmodified CRC membrane, negatively charged version of CRC membranes having different spacer arm lengths were found to increase the rejections of NOM and heavy metal, and at the same time decreases the flux decline.

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Contents

Table of Figures

Table of Tables

Nomenclatures

MF	Microfiltration
m_p	Mass of permeate sample
$\dot{v}$	Volumetric flowrate of permeate sample
ΔP	Applied pressure
ED	Electrodialysis
FA	Fulvic
HA	Humic acid
HS	Humic substances
J_v	Flux with solution under a given set of operating conditions
L_p	Membrane hydraulic permeability
MWCO	Molecular Weight Cut Off
NF	Nanofiltration
NOM	Natural Organic Matter
CRC	Composite Regenerated Cellulose
RO	Reverse Osmosis
t	Filtration time
UF	Ultrafiltration
ρ	density of water

Chapter 1. Introduction

In China, the demand for water is anticipated to grow approximately 63 percent by 2030 — gallon for gallon, more than anywhere else on this planet. Northern China has long been short of water, and fast-growing cities like Beijing and Tianjin have already reformed to extensive recycling and conservation programs to resolve the need. Besides that, the latest goal, according to Chinese government's order, is to quadruple water production, by 2020, from 680,000 cubic meters in 2011, or 180 million gallons a day to as many as three million cubic meters, or about 800 million gallons (Wines, 2011). Thus, water treatment is recently recognized as one of the most essential industry in China. Although water sources in China have been considered clean and safe to drink since 1985, they are seriously worsened these days. The main pollutants in water sources for towns and cities had transformed from microorganisms to natural organic matters (NOM) and heavy metal ions. NOM can build up in the human body, damage human health gradually, and lead to cancer, birth defects, and mutations in serious cases (Gong, Jing, Liu, Hongqiao, 2013). Heavy metal can cause negative effect to human body such as cancer, kidney stones, or other health problems. Hence, appropriate water purification to remove NOM and heavy metal has been a crucial research focus in China.

Elaborately, water purification is the process of removing pollutants from untreated water to produce water that is adequate for its intended uses, particularly for human consumption. Depending on the quality of the water entering the plant and the required standard for output water, various water treatment methods can be applied in different communities and industries. Typically, a water purification plant operates several water treatment stages including pre-treatment, pH adjustment, coagulation and flocculation, sedimentation, filtration, and disinfection. Filtration is recognized as the final step that eliminates the remaining suspended particles and unsettled floc. One of the most popular type of filter used in filtration is membrane filter as it is widely applied in both drinking water and sewage due to its ability of removing particles having sizes as small as 0.001 µm (Nanofiltration). Membrane filtration has been explored as an attractive technology for potable water treatment in recent years as it provides a physical barrier that can effectively remove solids, viruses, bacteria, and other undesirable molecules. Its processes have excellent separation capabilities for attaining many of the existing and anticipated drinking water standards. Different types of membrane processes are utilized for different purposes of water treatment based on its size, shape, and characteristics. Some typical pressure-driven membrane processes are microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) membranes. As UF is one of the most popular methods in membrane filtration, many researchers have worked on enhancing its filtering ability in recent years.

Moreover, conventional water purification methods aim to kill only microorganisms. For instance, traditional UF membranes are applied to advanced water treatment to remove emulsified oils, metal hydroxides, colloids, suspended solids, and other large molecular weight material. Due to the large pore size, the ability of removing NOM and heavy metal using traditional UF is limited as it cannot effectively remove NOM and heavy metal, especially when they are coexisted. Hence, modifying UF membranes to stimulate simultaneous removal of NOM and heavy metal will be a valuable approach to water purification industry, especially with response to China's high demand of clean water. Furthermore, previous researches have already indicated that modified negatively charged regenerated cellulose (RC) membrane with larger spacer arm lengths have better removal of NOM, while reducing flux decline during filtration process. Also, high binding rate of heavy metal to humic substances, a major part of NOM, has been found to allow effective removal of both heavy metal and NOM by UF membrane. Thus, leveraging from previous studies, it is attractive to investigate whether negatively charge UF with different spacer arm lengths can remove NOM and heavy metal simultaneously.

The scope of this project involves modifying UF membranes with spacer arm lengths of 3 and 9 to remove of humic acids (HA), a main component of NOM, and Ni, a common heavy metal in water. The objective of this project is to explore the opportunity of using charged UF membrane at different spacer arm lengths for the effective removal of NOM and heavy metal in water. To achieve the objective, the following goals have been outlined:

(1) Study previous methods of removal NOM and heavy metal using membrane filtrations
(2) Develop a methodology along with conducting series of experiments to determine appropriate spacer arm length to enhance possibility of removing NOM and heavy metal simultaneously from water
(3) Discuss the results and provide appropriate recommendations

This project is divided into five chapters that detail the developmental stages of the project and its approach. This Chapter presented the problem statement, scope, and objective of the project. Chapter 2 reviews the literature to provide a background of relevant topics. Chapter 3 discusses the methodology including related techniques and series of experiments to be employed. Chapter 4 describes the main results and discussion of the project. Finally, an overall conclusion and recommendations are provided in Chapter 5 to review the impact of the project.

Chapter 2. Backgrounds

2.1 Water industry in China

As China is identified as having the highest population in the world, it is not surprised to become the world's biggest water user, accounting for 13 percent of the world's freshwater consumption. Fortunately, China have many sources of fresh water that its people have relied on for centuries, including rivers, lakes, rain, and aquifers. As a country undergoing such rapid urbanization and economic development, clean water, however, is becoming more and more scarce (Sekiguchi, 2006). Approximately 190 million of Chinese are recorded sick from drinking contaminated water. 300 million rural Chinese have lack access to safe drinking water. About 50% of major cities in China did not meet the government drinking-water quality standard (China Water Risk, 2013). Furthermore, although approximately 97% of China's urban residents enjoy access to tap water, only 60% of China's population have access to running water and still fewer of these gain access to clean water (China industry: Water supply needs cleaning up, 2003). Therefore, water supply and quality is recognized as fundamental issue in China, which make water treatment one of the biggest industry in this country.

In order to utilize water purification plant efficiently, China must employ technologies that provide long- term dependable operation, use less chemicals, and have low operating cost. There are several proven technologies for water treatment, including clarification, granular media filtration, carbon adsorption, low-pressure membrane filtration, reverse osmosis (RO), membrane bioreactors (MBR) and disinfection. Particularly, membrane technology, which is commonly used as a final step in water treatment plant to remove the remaining suspended particles and unsettled floc, has been highly recognized due to its high efficiency and low cost. Hence, the development of membrane technology plays a crucial role in water treatment implementation in China to respond to its high- quality water demand.

2.2 Membrane technology in water treatment

2.2.1 History of membrane technology

Similar to other water treatment methods, membrane filtration has evolved from several researches and development phases to be proven and validated as cost-effective opportunity for a wide variety of feed streams in purification processes. The developments and improvements in membrane filtration continue as it gains more recognition on the ability of removing contaminants from the feed streams in different industries, particularly in water treatment plants (Asia, 2005). Although membrane filtration has been developed and well-recognized in recent years, it has already been researched for more than 200 years in the history, which is shown in figure 1.

The first recorded study of membrane filtration was in the middle of the 18th century when the relation between a semipermeable membrane and osmotic pressure was explored by Nollet (Nollet, 1752). By that time, more systematic studies on mass transport in semipermeable membranes were conducted. Later, at the beginning of the twentieth century, the first synthetic membrane was created by impregnating a filter paper with a solution of nitrocellulose in glacial acetic acid (Strathmann, H. , Giorno, L. , Drioli, E., 2006). These membranes were used mostly in microbiological laboratories in analytic applications.

In 1907, Bechold introduced term ultrafiltration which is forcing solutions at pressures up to several atmospheres through membranes prepared by impregnating filter paper with acetic acid collodion. However, ultrafiltration membrane was not advanced until early 1960s. In 1930s, electrodialysis membrane was created with the development of the first reliable ion-exchange membranes which have both good electrolyte conductivity and ion-permselectivity.

Then, the first membranes developed for reverse osmosis desalination and other applications, also known as RO membranes, were manufactured as flat sheets and installed in a so-called spiral wound module. RO membranes were produced in three different configurations, i.e. as flat sheets, as hollow fibers or capillaries, and as tubes. In today's' RO desalination plants, mainly spiral wound modules are used, while hollow fiber membranes modules are utilized in gas separation and pervaporation (Asia, 2005).

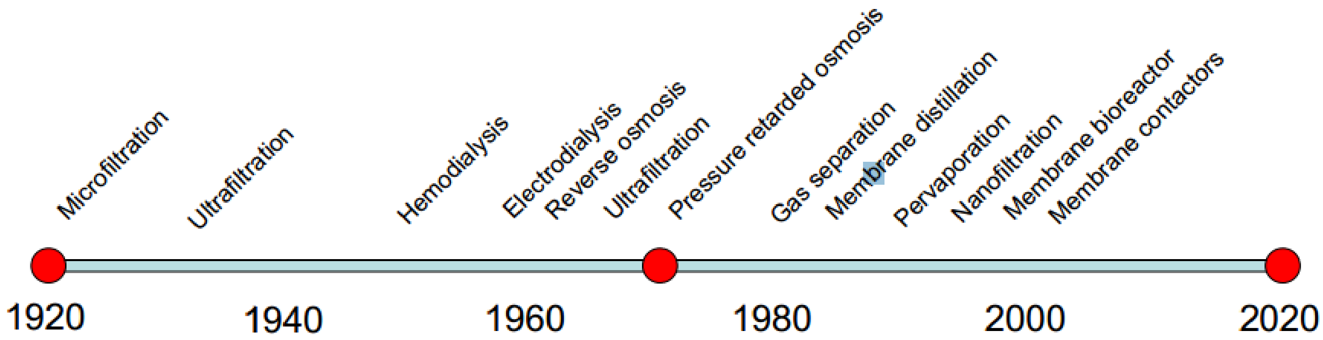

Figure 1: History of membrane processes (Strathmann, 2008)

History of membrane research in China

While the world research have focused on membrane processes since 18 century, China started late with ion exchange membranes in 1958. Researches on RO membranes were advanced starting in approximately 1965. Then, a national joint research project on sea water desalination began in 1967. This played a crucial role in training research team and laid a good foundation for the evolution of membrane science and technology in China. In the seventies, an outstanding period for membrane research and development was initiated. Membranes and its related modules for electrodialysis ED, RO, UF and MF had mostly been developed during that period of time (Drioli, E., Macedonio, E. F., 2008).

2.2.2 Membrane filtration in industry

Along with the development in membrane processes, the first membrane filtration systems were first installed in the mid-1980s. The first commercial membrane systems were constructed to treat high value feed streams including wine, juices and water for pharmaceuticals (Asia, 2005). In mid-1990s, further development and cost improvements have motivated membrane filtration plants to become viable on low value feed streams such as potable water and secondary effluent.

Generally, membrane filtration processes can be operated without heating; thus it uses less energy than conventional thermal for separation processes including distillation, sublimation or crystallization. Cold separation using membrane technology is widely utilized in the food technology, biotechnology and pharmaceutical industries. For instance, membrane processes are applied on dairy and food plant waste streams, potato flume water, and recovery of spent cleaning solutions. Membrane filtration is popularly used in water purification and water treatment (Filtration, 2013). Figure 3 shows the global distribution of membrane processes in drinking and industrial water production throughout years. It can be seen that the application of membrane processes in water treatment, especially RO membranes, has increased rapidly due to an increase in water consumption (figure 3).

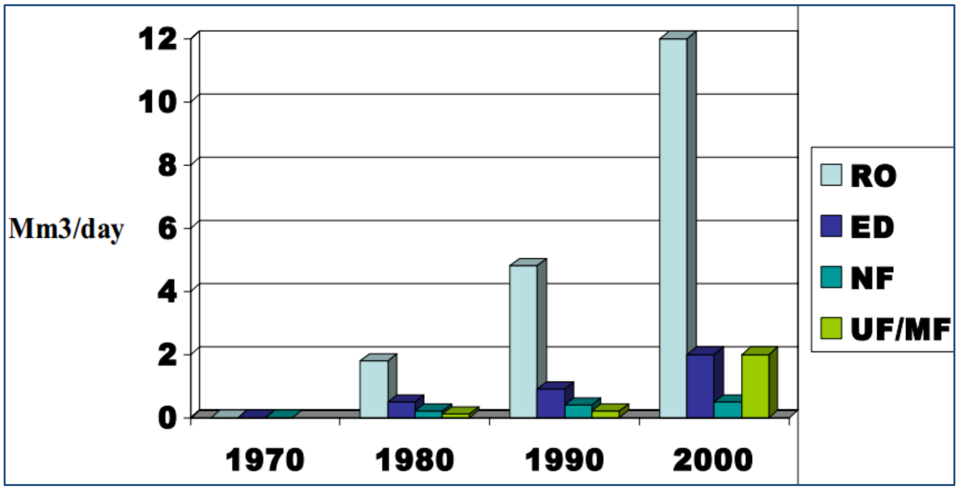

Figure 2: Total installed capacity of different membrane processes in drinking and industrial water production in the world, 2010

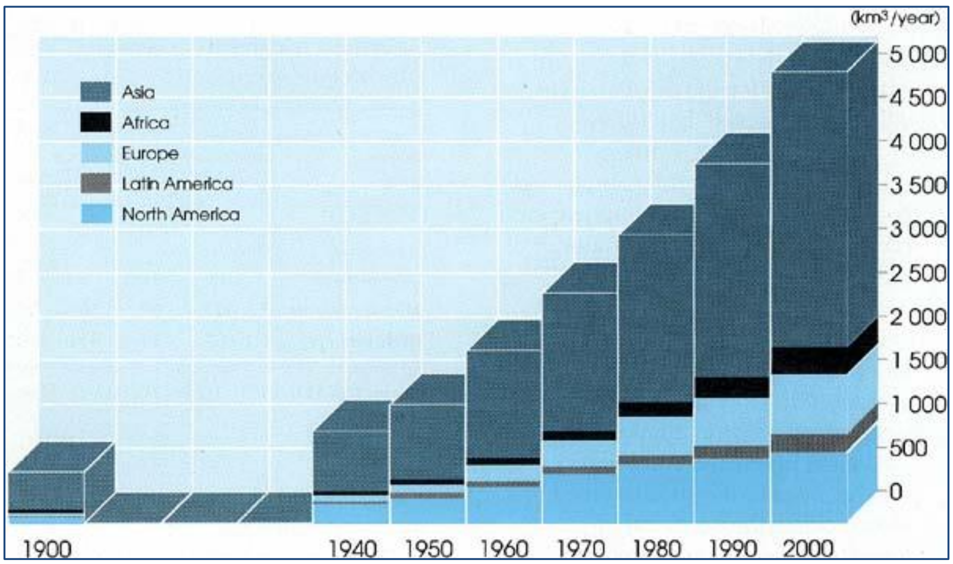

Figure 3: Global water consumption

Membrane in China industry

In recent years, new technologies and processing techniques on membrane production are continuously discovered and invented. Membrane application is constantly developed for more industrial fields, particularly water treatment including seawater desalination, recycling wastewater, and purifying water. In China, about 90% membrane separation engineering companies are involved in manufacturing equipment for the production of industrial pure water, high pure water and civilian pure water (Drioli, E., Macedonio, E. F., 2008).

2.3 Common types of membrane filtration

Membranes utilized in various applications differ mostly in their structures, functions, and the ways they are operated. Different types of membrane are chosen depending on the particle sizes and the properties of contaminants. For instance, a general membrane filtration selection based on questions relevant to contaminant characteristics is shown in figure 4.

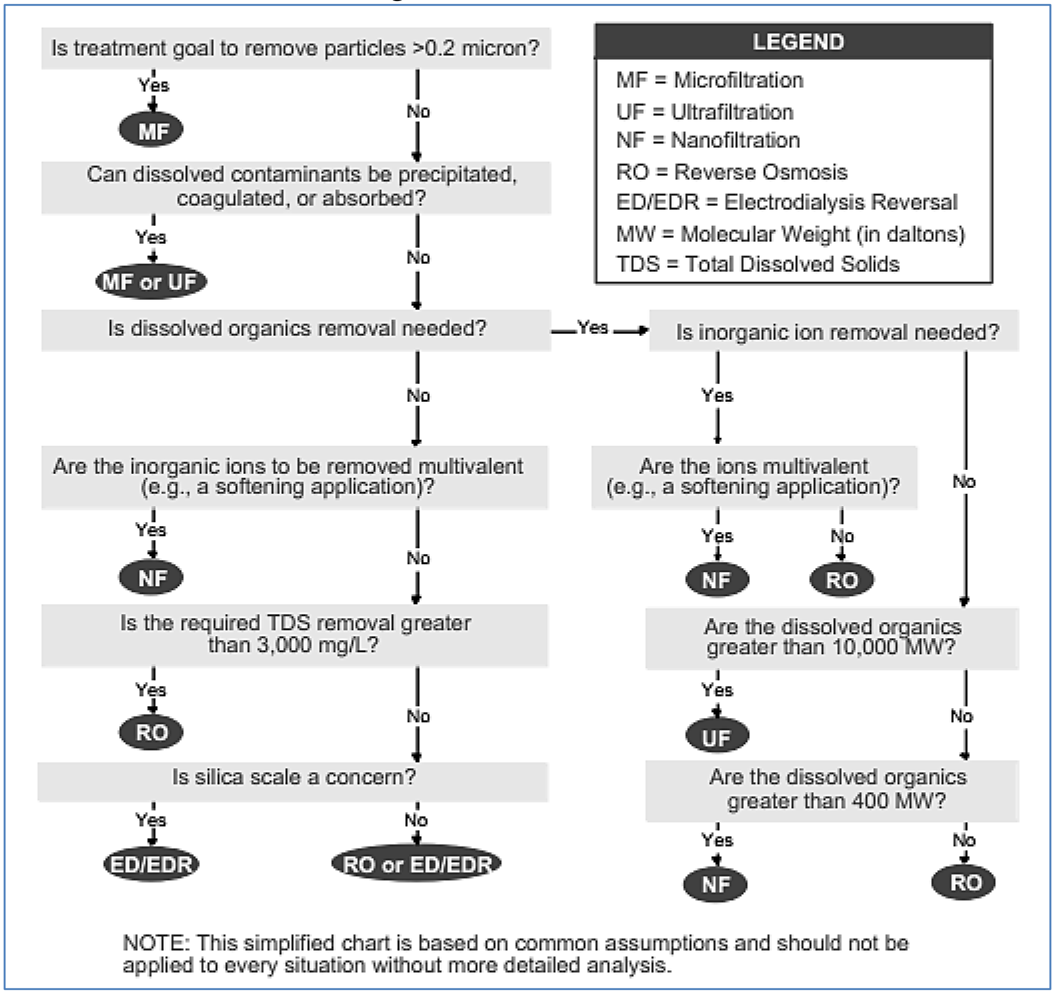

Figure 4: Generalized membrane selection chart (Brief, 1999)

2.3.1 Ultrafiltration membranes

Ultrafiltration membranes have pore size of approximately 0.002 to 0.1 microns and MWCO of approximately 10,000 to 100,000 Daltons (AiChE, 2013). It is used mostly in the pressure-driven separation of contaminants including colloids, particulates, and high molecular mass soluble species, from water. UF membranes can remove all microbiological species as well as some viruses and allows most ionic inorganic matter to pass through and retains particulates and ionic organic species. This membrane can eliminate many water-soluble organic matters as well as microbiological through only a single process (Strathmann, H. , Giorno, L. , Drioli, E., 2006).

As UF membranes are designed to remove suspended and dissolved macromolecular solids from fluids, particularly water, the commercial UF membranes can accept feed water that carry high loads of contaminants. Hence, UF is popularly used in different industries, which is displayed in figure 5. From figure 5, approximately 60% of UF membranes are employed in drinking water treatment. About 18% of its total usages is for large industrial water treatment, and 15% of UF membrane is for waste water treatment.

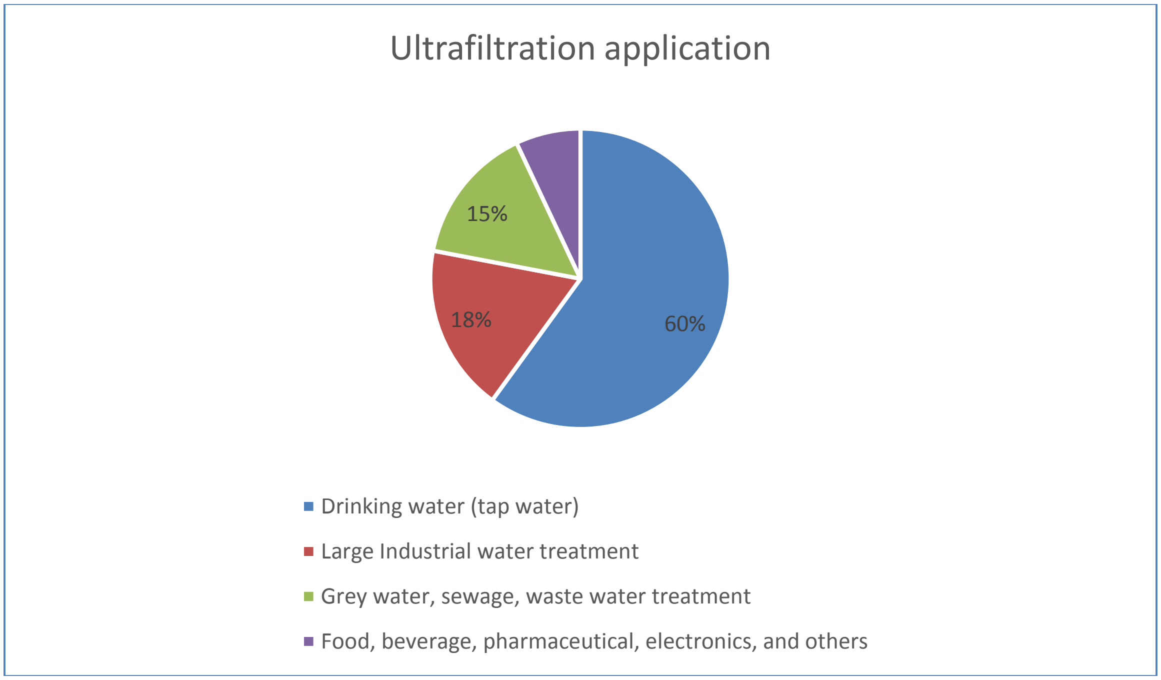

Figure 5: Distribution of UF usage in different industry

2.3.2 Other types of membrane filtration

Reverse Osmosis membranes

Reverse osmosis is one of the most common and effective water treatment systems that use RO membranes or a semipermeable membranes. As RO membranes can remove many types of molecules and ions from solutions, it is applied in both industrial processes and potable water production. RO membranes are effectively non-porous; therefore, it can exclude particles and even many low molar mass species such as salt ions, organics (Sagle, A., Freeman, B., 2004). The mechanism of RO membrane process is "selective" as it will not allow large molecules or ions through the pores, but will allow smaller components such as the solvent to pass freely. RO membrane can remove nearly all inorganic particles from water. It can also eliminate radium, NOM, pesticides, cysts, bacteria, and viruses efficiently (Brief, 1999). RO membranes are used more effectively if it is in series with other filtration processes.

Microfiltration membranes

Microfiltration membranes have pore size of approximately 0.03 to 10 microns, MWCO of greater than 100,000 Daltons, and low heat water operating pressure from 15 to 60 psi (AiChE, 2013). MF membranes are typically used to remove sand, silt, clays, and some bacteria species. As there is increasingly stringent requirement for eliminating particles and microorganisms from drinking water, the demand of MF membrane is increased. Other applications of MF membranes are to remove fouling potential as a pretreatment to RO and NF and to desalt or remove hardness from ground water. Unlike UF membrane, MF membrane doesn’t have the ability of removing appreciable densities of viruses.

Nanofiltration membranes

Nanofiltration membranes have pore size of about 0.001 microns and MWCO of 1000 to 100,000 Daltons (AiChE, 2013). It is recognized as the crossover technology between UF and reverse osmosis RO. Similar to RO, NF is a pressure driven separation and the operating pressure required for NF is usually higher than those of the MF and UF. NF membranes are used in a wide range of drinking water, wastewater, and industrial applications as it can effectively remove hardness from 50% to 97% depending on the membrane selected.

In summary, the ranks in pore sizes of membrane processes is shown in figure 6. MF has the biggest pore size while RO has the smallest one. As mentioned above, the pore size of UF is in a large range. Furthermore, NF has pore size range in between those of RO and UF.

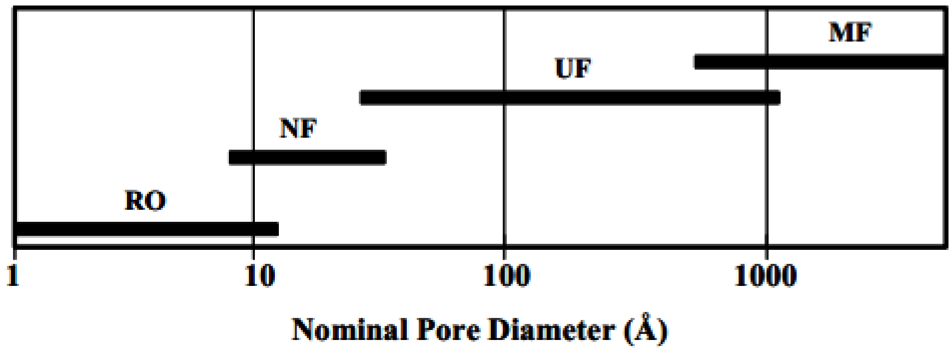

Figure 6: Range of Nominal Pore of Different Types of Membranes (Sagle, A., Freeman, B., 2004)

2.4 Enhance ultrafiltration membranes

Generally, selectivity and permeability occur as a trade-off in traditional membranes. The higher the permeability, the smaller the membrane area required to treat a given amount of contaminant, thereby, reduce the capital cost of membrane unit. Higher selectivity results in better purification process through membrane. However, membranes that are more permeable are less selectivity and vice versa (Freeman, 1999). Hence, modifying membrane that can enhance both selectivity and permeability have been an attractive topic to many researchers.

Recent studies have shown that electrostatic interaction between charged substances, including protein and humic acid, and membranes can result in large effects on product retention and system performance. Pollutant retention within membrane filtration has been studied as not depending only on pore size but also the electrostatic interaction between a negatively charged membrane and the negatively charged pollutant solute which has size much smaller than that of the membrane's pore (Bhattacharyya, D., McCarthy, J. M., Grives, R. B., 2004). Thus, charged UF membrane, or "enhanced ultrafiltration", has been learned to provide much higher product preservation than traditional membrane as it is able to support much better incorporation of product yielded and membrane hydraulic permeability than conventional UF (Shao, J., Zydney, A. L. , 2004).

Furthermore, previous studies have already shown that adding spacer arm length to negative-charge membrane also play a crucial role in enhancing the ability of removing HA from water. Spacer arm length is recognized as number of $-CH_2-$ group added to the charged membrane to increase charges on the membrane surface. As UF membrane with spacer arm length of 9 has higher zeta potential value, or more charges on its surface, than that of membrane with spacer arm length of 3 and unmodified membrane, it provides higher HA removal (Shao, Jiahui; Zhao, Ling; Chen, Xiuwen; He, Yiliang, 2013). The mechanism of adding spacer arm length to negatively charge membrane is shown in figure 7.

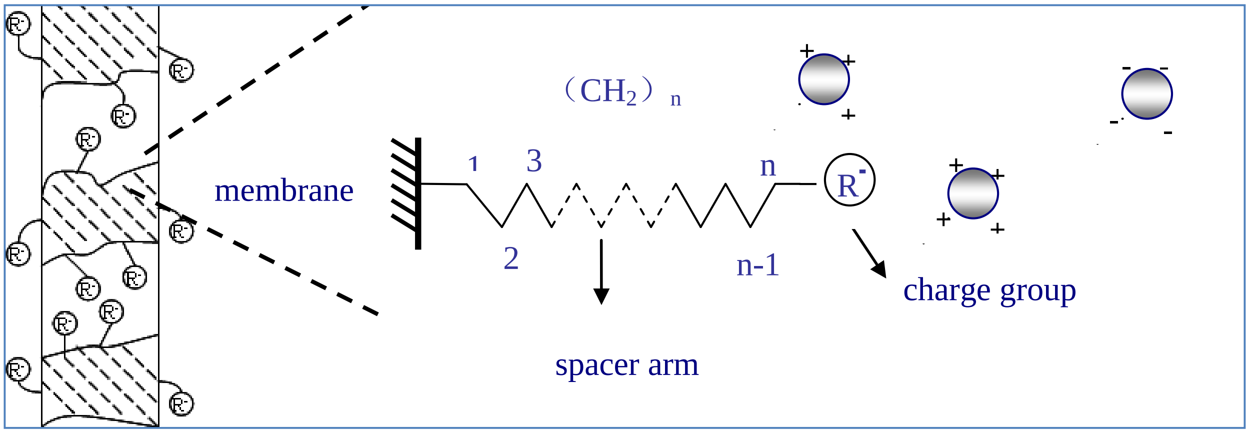

Figure 7: Mechanism of adding spacer arm length to negatively charged membrane

Also, zeta potential values of membranes with different spacer arm lengths are also provided in table 1.

Table 1: Zeta potential values of membranes with different spacer arm lengths

Membrane	Zeta potential (mV)
Unmodified	-0.45
n=3	-16.09
n=9	-25.67

2.5 Water treatment industry

Nowadays, about 800 million people or approximately one in nine people have limited contact to an improved water sources. "Lack of access to clean water and sanitation have kill children at a rate of equivalent of a jumbo jet crashing every four hours" (Water, 2013). Therefore, as playing an important role in human life, water treatment industry has been developed unceasingly and quickly.
Among different types of pollutant particles, special attention in water treatment is given to the removal of natural organic matter (NOM), which is a precursor of disinfecting by-products, and heavy metal.

2.5.1 Natural Organic Matter (NOM) removal

NOM, which is typically found in surface water, may cause problems in water treatment plants and all the way to the consumers as it can react with major disinfectants to form disinfection byproducts and create complexation with metal and hydrophobic synthetic compounds (Zularisam, A.W., Ismail, A.F., Salim, R. , 2006). Problematically, NOM cannot be readily rejected during UF as UF membranes have relatively larger pore size than the size of NOM (Krasner, S.W., Weinberg, H.S. , 2006). Also, the NOM concentration in drinking water resources is recognized to increase continuously since 1990 due to the result of climate warming, changes in soil acidification, severe drought seasons, intensive rain events, and other factors (Korth, A., Fiebiger, C., Bornmann, K., and Schmidt, W., 2004).

Furthermore, NOM is a heterogeneous mixture of biopolymers and their degradation products of plants and animal residues; thus, NOM consists of components with diverse properties and molecular sizes. In drinking water, NOM which can bind and transport harmful contaminants, causes aesthetic concerns such as color, taste and odor (Metsämuuronen, S., Sillanpää, M., Bhatnagar, A., Mänttäri, M., 2013). The great inconsistency in NOM composition makes it problematic to be completely eliminated from drinking waters. Traditional treatments including coagulation and sand filtration are capable of removing more than 50% of highly hydrophobic and high molar mass compounds, but less than 25% of low molar mass compounds (Edzwald, J.K. and Tobiason, J.E., 1999; Brief, 1999; Matilainen, A., Vepsäläinen, M., and Sillanpää, M., 2010). As the cost of membrane filtration has decreased significantly in recent years, membrane systems for portable water has been employed in various countries to reduce the NOM content in drinking water.

Aquatic NOM contains humic substances (HS) (include humic and fulvic acids), which play roles as the major part of NOM, is typically about 50% of the dissolved organic matter. Typically, HS exist in natural waters in concentrations ranging from 20 μg/l in groundwaters and up to 30 mg/l in surface waters. Humic acid (HA) is a subcategory of HS, which is soluble in water at pH greater than 2. This compound has a complex structure containing both phenolic and carboxylic groups; hence, it carries negative charges in natural waters (Jones and Bryan, 1998 and Suffet and Maccarthy, 1989). However, only few studies have focused on enhancing the removal of HA such as using the cationic quaternary ammonium compound cetyl trimethyl ammonium bromide (CTAB), or flotation of HA with CTAB and ethanol.

2.5.2 Heavy metal removal

Similar to NOM, removing undesirable metal from water system is a very crucial and challenging task for environmental and chemical engineers. Heavy metals are elements having atomic weights between 63.5 and 200.6 with a specific gravity greater than 5.0. Unlike NOM, heavy metals are not biodegradable and tend to accumulate in living organisms. Many heavy metal ions are recognized to be toxic or carcinogenic, including zinc, copper, nickel, mercury, cadmium, lead and chromium (Fu,Fenglian; Wang,Qi, 2011). Unnecessary absorption of heavy metals by plants can lead to toxicity in human daily nutrition, and cause chronic diseases. Besides that, high concentrations of heavy metals in soil can negatively affect crop growth as they interfere with metabolic functions in plants, including physiological and biochemical processes, even leading to death of plants (Garbisu and Alkorta, 2001; Schmidt, 2003; Schwartz et al., 2003)

Plenty of methods have been explored for effective heavy metal removal from waters such as chemical precipitation, ion exchange, adsorption, membrane filtration, and electrochemical technologies (Hua,Ming; Zhang,Shujuan; Pan,Bingcai; Zhang,Weiming; Lv,Lu; Zhang,Quanxing, 2012). Among these techniques, membrane filtration is recognized as a great opportunity for heavy metal removal thanks to its efficiency, easy operation, and space saving.

Recognized as a popular membrane processes, UF works at low transmembrane pressures for the removal of dissolved and colloidal material. However, since the pore sizes of UF membranes are typically larger than the heavy metal ions or molecular weight complexes, UF membranes sometime allow the metal particles to pass freely through itself. Thus, enhanced UF has been proposed to obtain high removal of metal ions. Metal removal efficiency by enhanced UF depends on the characteristics and concentrations of the metals and surfactants, solution pH, ionic strength, and parameters related to membrane operation (Fu,Fenglian; Wang,Qi, 2011).

2.5.3 Simultaneously removal of NOM and heavy metal

Many methods have been proposed to effectively remove NOM or heavy metal from water (Fu,Fenglian; Wang,Qi, 2011; Hua,Ming; Zhang,Shujuan; Pan,Bingcai; Zhang,Weiming; Lv,Lu; Zhang,Quanxing, 2012; Matilainen, A., Vepsäläinen, M., and Sillanpää, M., 2010); however, not that many researches focus on removing heavy metal and water simultaneously.

An effective way of removing NOM from water by negatively charged membranes of with different spacer arm lengths and charge groups were proposed by (Shao, Jiahui; Zhao, Ling; Chen, Xiuwen; He, Yiliang, 2013) as charged RC membranes can provide much higher NOM retention than a neutral unmodified membrane. In addition to surface charge density of the membrane surface, specific coupling chemistry along with spacer arm length (length of hydrocarbon chain between the solid support and the functional ligand) can also affect the overall system performance (Shao, Jiahui; Zhao, Ling; Chen, Xiuwen; He, Yiliang, 2013). It has also been found that negatively charged version of RC membranes having different spacer arm lengths yielded larger rejection of HA in NOM.

Additionally, rejection of heavy metal such as Pb (II), Cu (II), Ni (II), and Co (II) in the presence of HA and FA have been studied in recent years. As HS increases with pH and considered as the substances biding of small heavy metal ions that are rejected by semi-permeable membranes, simultaneous removal of metals and HS by UF from solutions of varied pH and concentration of heavy metals have been studied. Therefore, investigating the effect of spacer arm lengths and charge groups on removal of NOM and heavy metal simultaneously during filtration, which cannot be found in any literature, is attractive to study.

Chapter 3. Methodology

3.1 Outline of previous studies

The experiments conducted for this project are supported by the theories and data from previous studies as the following.

- Negatively charged UF membranes have high rejection of humic acid and less flux decline
- HA can involve in many environment processes, especially in binding, transport and deposition of inorganic and organic pollutants. This feature of HA can be used for trace metal removal in water containing NOM and HM.
- Concentrations of NOM in drinking water, mainly HA, range from 20 µg/L (groundwater) to 30 mg/L (surface water). The content of humic acid in average water is 10 mg/ L, accounting for the total NOM in water for 50% to 90%.
- Flame atomic absorption spectrophotometry can directly determine nickel absorbance in industrial wastewater. This method is suitable for industrial wastewater and contaminated water samples. The minimum detectable concentration was 0.05 mg/L, and the concentration range of the linear calibration curve was from 0.2 to 5.0 mg/L.

3.2 Materials and Equipment

To conduct the experiments for this project, the following materials and equipment are employed.

3.2.1 Materials

- Membranes utilized for UF processes were CRC membranes with nominal MWCO of 30 kD and 100kD, from Millipore Corporation. The membranes have diameter of 25 mm.
- Charged modification reagents, from Sigma, were used to add charges and spacer arm lengths to UF membranes, which were:
  - 97% 3-bromopropane sulfonic acid sodium salt, $Br(CH_2)_3SO_3Na$
  - 97% 6-chloro-1-hexanol, $C_6H_{13}ClO$
- Solutions of HA and Ni used as feed water in the UF processes had the following concentrations:
  - HA-representative of NOM: 1mg/L, 2 mg/, 4 mg/L, and 8 mg/L
  - Ni- representative of heavy metal: 0.5mg/L and 1 mg/L
- pH modification reagents used to adjust solution pH were:
  - 0.1 M HCl
  - 0.1 M NaOH

3.2.2 Equipment

To support the experiment, the following equipment were employed.

- pH indicator was used to indicate the pH of solutions of HA and Ni in the process of changing solution pH, which is shown in figure 8.

Figure 8: pH indicator

- Shaking water bath was employed to increase the binding rate of HA and Ni in the feed solution, which is shown in figure 9.

Figure 9: Shaking water bath

- Membrane stir cell including an internal magnet stirrer, was used to conduct UF separation (figure 10). The unit is an Amicon Corporation Model 8010 unit model, which has the maximum volume capacity of 10 mL and was manufactured for polysulfone.

Figure 10: Millipore Corporation Model 8010 Stirred Cell

- Spectrophotometer was used to measure the absorbance of HA, which is shown in figure 11.

Figure 11: Spectrophotometer

- Atomic absorbance used to measure Ni absorbance is displayed in figure 12

Figure 12: Atomic absorbance

- Beckman Coulter Delsa Nano C Zeta potential/submicron size analyzer was used to measure zeta potential of membrane (figure 13)

Figure 13: Beckman Coulter Delsa Nano C Zeta potential

3.3 Experiments

3.3.1 Membrane preparation

The CRC membranes with nominal MWCO of 30 kD and 100 kD were modified by changing the overall charges of the membranes and adding the spacer arm lengths to the charged groups. First, membranes were flushed with pure water to remove any chemical reagents from membrane pore structures. Then, membranes were soaked in isopropyl alcohol (IPA) in a small glass bottle and let sit for at least an hour to clean any chemicals from manufacturing processes. After that, membranes were washed with pure water again and preserved in either sodium hydroxide, NaOH, or sodium hydrosulfide, $NaSO_{3,}$ for further modification experiments.

Negatively-charged form of the membranes can be made in the laboratory by the adding covalent negatively charged sulphonic acid groups with different spacer arm lengths to the surface of the membrane (Shao, Jiahui; Zhao, Ling; Chen, Xiuwen; He, Yiliang, 2013). To modify membranes with spacer arm lengths of 3, only one- step chemical reaction was needed to obtain both negative charge and spacer arm length of 3. The pretreated membrane was soaked in 2M solution of 3-bromopropanesulfonic acid sodium salt for approximately two days. For membranes with spacer arm length of 9, two steps of chemical reaction were required. First, six –CH2- groups were added as the linker between the membrane and the charged group. The pretreated membranes were placed in a 2 M solution of 6-chloro-1-hexanol, for over 48 hours.

After that, membranes were taken out, flushed with pure water, and immersed in a 2 M solution of 3-bromopropanesulfonic acid sodium salt for approximately two more days (similar to modification reaction for membrane with spacer arm length of 3). Then, both types of membranes, along with unmodified membranes, were stored in NaOH or NaHSO3 until use.

Besides that, 2M 3-bromopropanesulfonic acid sodium salt and 2M 6-chloro-1-hexanol solutions were made from stock solution as mentioned in section 3.2.1.

- $\mathbf{2.32g}\ of\ 97\%\ Br(CH_2)_3SO_3Na + \mathbf{5mL}\ of\ 0.1\ M\ NaOH \rightarrow \mathbf{2\ M}\ Br(CH_2)_3SO_3Na$
- $\mathbf{1.33mL}\ of\ 97\%\ 6 - Chloro - 1 - hexanol + \mathbf{5mL}\ of\ 0.1\ M\ NaOH \rightarrow \mathbf{2M}\ 6 - Chloro - 1 - hexanol$

3.3.2 Solution preparation

1000 mL solution of different HA-Ni ratios was prepared new every day. pH of solution was adjusted to either 3.5 or 7 by adding 0.1M hydrochloric acid or 0.1 M sodium hydroxide to the solution. Prior to ultrafiltration, solutions were kept in a shaking water bath at 25 ◦C with gentle agitation for approximately 12 hours to reach an equilibrium state for the HA–metal ion system. Besides that, ionic strength of HA-Ni solutions can be adjusted by adding calculated quantities of 0.1M potassium chloride.

3.3.3 Ultrafiltration experiment:

To conduct the ultrafiltration experiments, the membrane was placed in the stir cell with the smooth side of membrane facing up after being washed by pure water. Air was ejected out by elevating the HA-Ni solution or pure water that fill up the stir cell, while opening the black level on the stir cell. Then, N_2 gas tank was opened to adjust pressure of air to stir cell. At each pressure, the dead volume was extracted out from beneath the membrane, and the permeate was collected in the beaker. Once the ultrafiltration process reached its steady state, the timer was started, and three samples of permeates were collected consecutively, in different sample tubes for every 6 minutes. After the third sample was collected, i.e. at 18^{th} minute, the pressure was turned off and the solution in the stir cell was collected in sample tube as the fourth sample for given pressure. The stir cell was then dissembled, and all parts of the stir cell and the membrane were washed with pure water at least three times. The ultrafiltration experiment was repeated at different pressure, ionic strength, and HA-Ni ratio. Besides that, additional samples were collected from the bulk solution before and after each experiment. These solution concentrations are then averaged and used as feed concentrations.

Three different membranes were run with the ultrafiltration experiment including unmodified membrane, membrane with spacer arm length of 3, and membrane with spacer arm length of 9. Different feed solutions were used based on varied ionic strength of 0 mM, 10 mM, and 50 mM KCl as well as varied HA-Ni ratios as stated in section 3.5.

The experiment setup including nitrogen gas tank, pressure gauge, stir cell, solution bottle, and timer, was illustrated in figure 14.

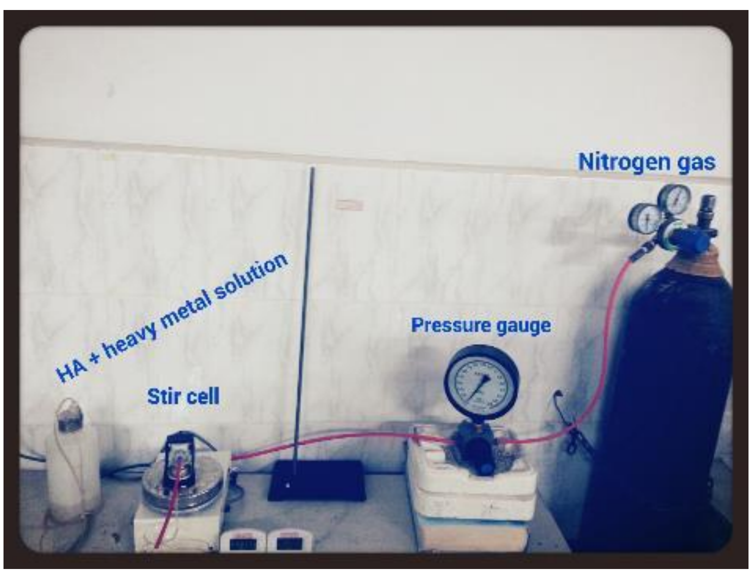

Figure 14: Equipment Setup

3.3.4 Analysis

After ultrafiltration experiments, the collected permeate samples were weighted to calculate the membrane flux. The absorbance of HA was determined by testing each sample by the UV spectrophotometer at wavelength of 240 mm. The absorbance of Ni was identified by testing the mixture of three samples collected at the same pressure by the atomic absorbance. The rejection of HA and Ni using ultrafiltration membranes can be calculated based on formula proposed in section 3.4

3.4 Theoretical

3.4.1 Membrane Analysis

Pure water membrane flux, L_p, can be calculated using the following equations:

$$\boldsymbol{L_p = \frac{J_v}{\Delta P}} \quad (1)$$

And

$$\boldsymbol{J_v = \frac{\dot{v}}{A}} \quad (2)$$

Where $\dot{v}\left[\frac{cm^3}{s}\right]$ is the volumetric flowrate of the permeate, A is the membrane surface area (490 mm^2), and $J_v\left[\frac{m}{s}\right]$ is the volumetric flux of permeate.

Also, volumetric flowrates of pure water during UF were computed based on the mass of collected sample and the water density as in equation (3)

$$\boldsymbol{\dot{v} = \frac{m_p}{\rho \Delta t}} \quad (3)$$

Where m_p $[g]$ is the mass of the permeate sample, ρ $\left[\frac{g}{cm^3}\right]$ is the density of water, and Δt $[s]$ is the sample collection time

3.4.2 Rejection rate of HA and Ni Analysis

The rejection of HA or Ni can be calculated based on formula (4)

$$\boldsymbol{Rejection = 1 - \frac{Abs\ HA\ (or\ Ni)_{sample}}{Abs\ HA\ (or\ Ni)_{stir\ cell}}} \quad (4)$$

Where

$Abs\ HA\ (or\ Ni)_{sample}$ is the absorbance of HA or Ni measured from water samples after ultrafiltration

$Abs\ HA\ (or\ Ni)_{stir\ cell}$ is the absorbance of HA or Ni measured from solution in sir- cell after ultrafiltration experiment

Also, for membrane fouling experiment, the absorbance of HA or Ni in the stir cell can be calculated instead of being measured, by using the following formula.

$$\boldsymbol{Abs\ HA_{\ stir\ cell,n} = Abs\ HA_{\ stir\ cell,\ n-1} + \frac{(Abs\ HA_{\ original} - Abs\ HA_n) \times sample\ wt.}{V_{stir\ cell}}} \quad (5)$$

Where

$Abs\ HA_{\ stir\ cell,n}$ is the absorbance of HA in the stir cell after collecting sample n

$Abs\ HA_{stir\ cell,n-1}$ is the absorbance of HA in the stir cell after collecting sample n-1

$Abs\ HA_{\ original}$ is the absorbance of HA in the water sample collected after ultrafiltration experiment number zero (also known as initial or original sample)

$Sample\ wt.$ is the weight of sample n.

$V\ stir\ cell$ is the volume of the stir cell. In this experiment, $Vstir\ cell\ = \ constant\ = 16.8\ mL$

3.5 Goals

Studying the methodology of the ultrafiltration experiments, the following goals were made to be achieved within 6 weeks.

(1) Study effect of molecular weight cut-off (30kD and 100 kD) on rejection of HA and Ni at transmembrane pressure drop (ΔP) of 0.02, 0.04, 0.06, 0.10MPa using the feed solution of 2 mg/L HA and 1 mg/L Ni with different versions of membranes (unmodified membrane, negatively-charged CRC membranes with different spacer arm lengths (n= 3, 9))
(2) Study effect of charge group and spacer arm lengths on the rejections of HA and Ni using CRC 30kD, while feed solution is the same as in (1).
(3) Compare rejections of HA and Ni between pure and mixture solution fed to the ultrafiltration system
(4) Study effect of ionic strengths (0, 10, 50 mM KCl) on the rejections of HA and Ni by adding calculated amount of KCl to the feed solution with HA-Ni concentration of 2 mg/L – 1 mg/L.
(5) Study effect of different HA-HM ratio (HA=1 mg/L, 2 mg/L, 4mg/L, 8 mg/L and Ni = 0.5 mg/L, 1 mg/L, 2mg/L) on the rejections of HA and Ni
(6) Study Effect of pH（3.5 or 7.0）on the rejections of HA and Ni
(7) Obtain zeta potential value of each membrane (Beckman Coulter Delsa Nano C Zeta potential/submicron size analyzer)
(8) Obtain membrane pore size and size distribution of each membrane (PMI capillary flow porometer)
(9) Compare membrane fouling between different type of membranes

Chapter 4. Results and Discussions

4.1 Effect of molecular weight cut-off on rejections of HA and Ni

The effect of molecular weight cut-off on the rejections of HA and Ni were displayed in figures 15-17 for unmodified membranes, membrane with spacer arm length of 3, and membrane with spacer arm length of 9, respectively. The feed solution used for this series of experiments has concentration of 2 mg/L HA and 1 mg/L of Ni with pH of 7.

In figure 15, the rejection rates HA and Ni using unmodified CRC 100 kD are less than the those using unmodified CRC 30 kD at the same pressures. However, with unmodified CRC 30 kD, the membrane flux rates are lower than those with unmodified CRC 100 kD membranes. These results were expected due to the difference in pore sizes of 100 kD and 30 kD membrane as pore size of 100 kD membranes were larger than those of CRC 30 kD membranes. Therefore, unmodified CRC 30 kD membranes could retain more HA and Ni, which yielded to higher rejection rates of HA and Ni, compared to unmodified CRC 100 kD membranes. Similarly, modified CRC 30kD membranes with spacer arm lengths of 3 and 9 also produced higher rejection rates of HA and Ni and lower flux rates, compared to modified CRC 100 kD membranes with spacer arm lengths of 3 and 9, which are illustrated in figures 16 and 17. Besides that, as the pressure increased, the rejection rates of HA and Ni in ultrafiltration experiments decreased, which had been expected as well.

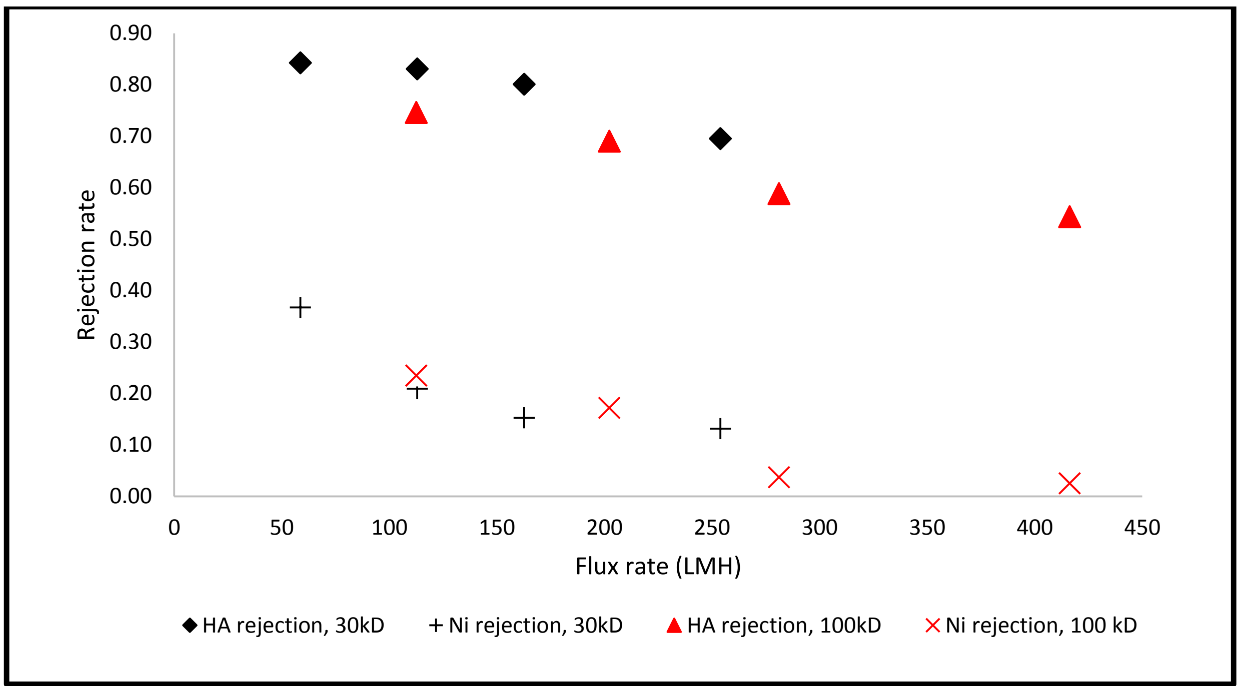

Figure 15: Comparison in rejection rates of HA and Ni between CRC 100 kD and CRC 30kD, unmodified

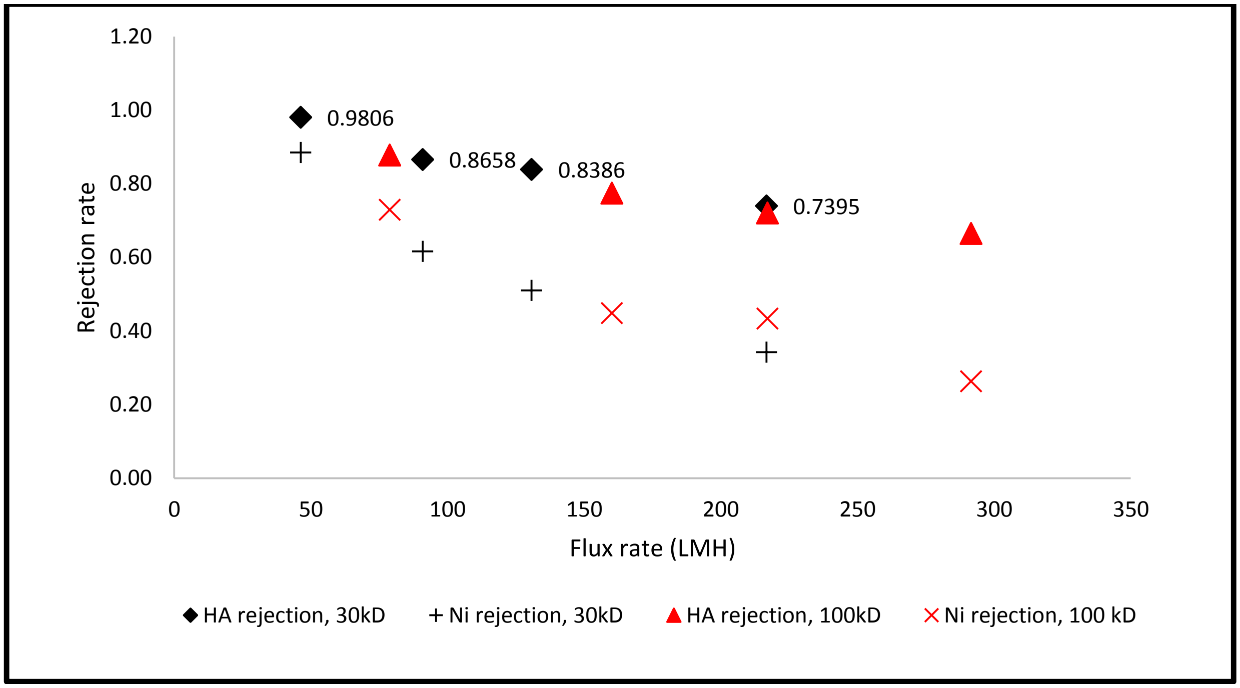

Figure 16: Comparison in rejection rates of HA and Ni between CRC 100 kD and CRC 30kD, n=3

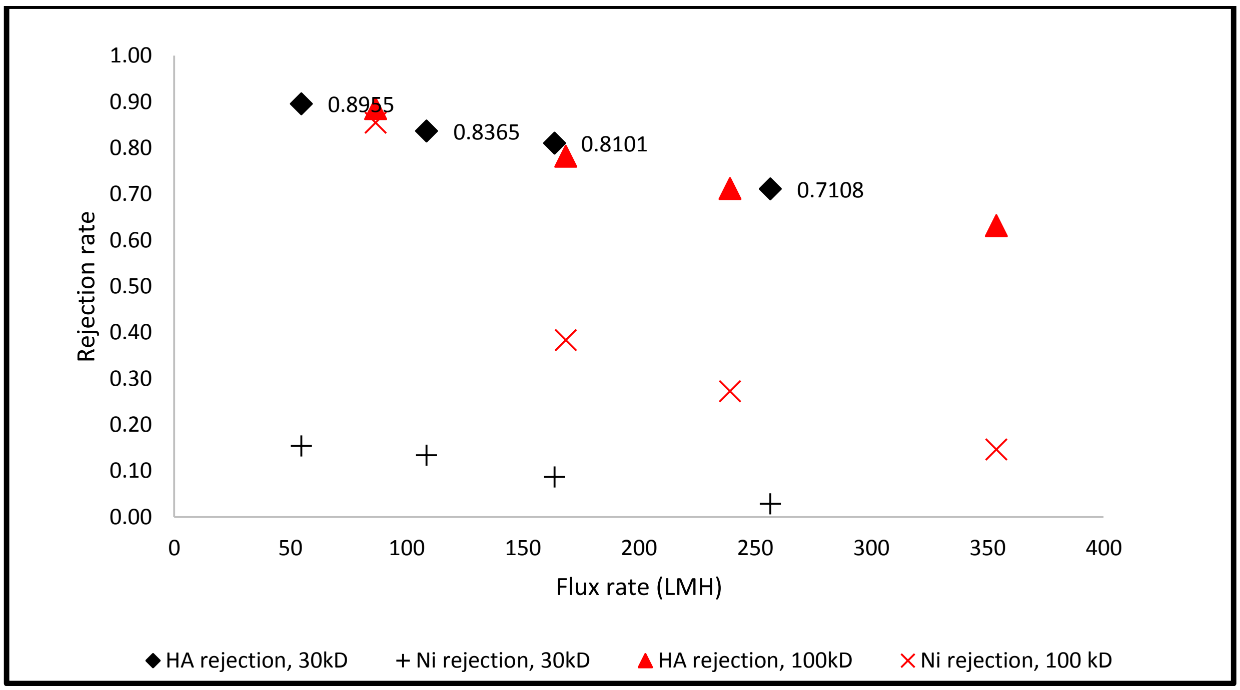

Figure 17: Comparison in rejection rates of HA and Ni between CRC 100 kD and CRC 30kD, n=9

4.2 Effect of spacer arm lengths on rejections of HA and Ni

From previous comparisons in rejection rate of HA and Ni between membranes with different MWCO, it was found that CRC 30 kD membranes yielded higher selectivity compared to CRC 100 kD membranes. Hence, it was attractive to learn which modification of CRC 30 kD membranes would yield the highest rejection rates of HA and Ni when conducting ultrafiltration experiment with feed solution of 2 mg/L HA and 1 mg/L Ni and pH of 7. Figure 18 showed the results of the comparison as unexpectedly, the rejections rate of HA between membranes with different spacer arm lengths are comparable to each other. Also, it is interesting that membrane with spacer arm length of 3 did provide the highest rejection rates of both HA and Ni, while membrane with spacer arm length of 9 yielded the lowest rejection rate of Ni when compared to all versions of membrane. These results happened to contradict to the previous studies where membrane with spacer arm length of 9 had more charges on membrane surface, which led to higher rejection rate of HA (Comparison of zeta potential in table 1). Also, as Ni was associated with HA, the rejection rate of Ni using membrane with spacer arm length of 9 was also expected to be the highest among those of the other membranes.

Hence, it was interesting to figure out whether the result represented a phenomenon or random mistakes. Two other membranes were modified with spacer arm lengths of 9 and utilized for the same experiments, however, similar results were found. Therefore, the 2-step modification of membrane with spacer arm length of 9 had been under investigation. It was suggested to check the chemicals used for the modification process as the solubility of current 6-chlorohexanol solution with NaOH solution was found to be much lower than expected. Because of such reasons, membranes with spacer arm length of 9 were not used for further experiments.

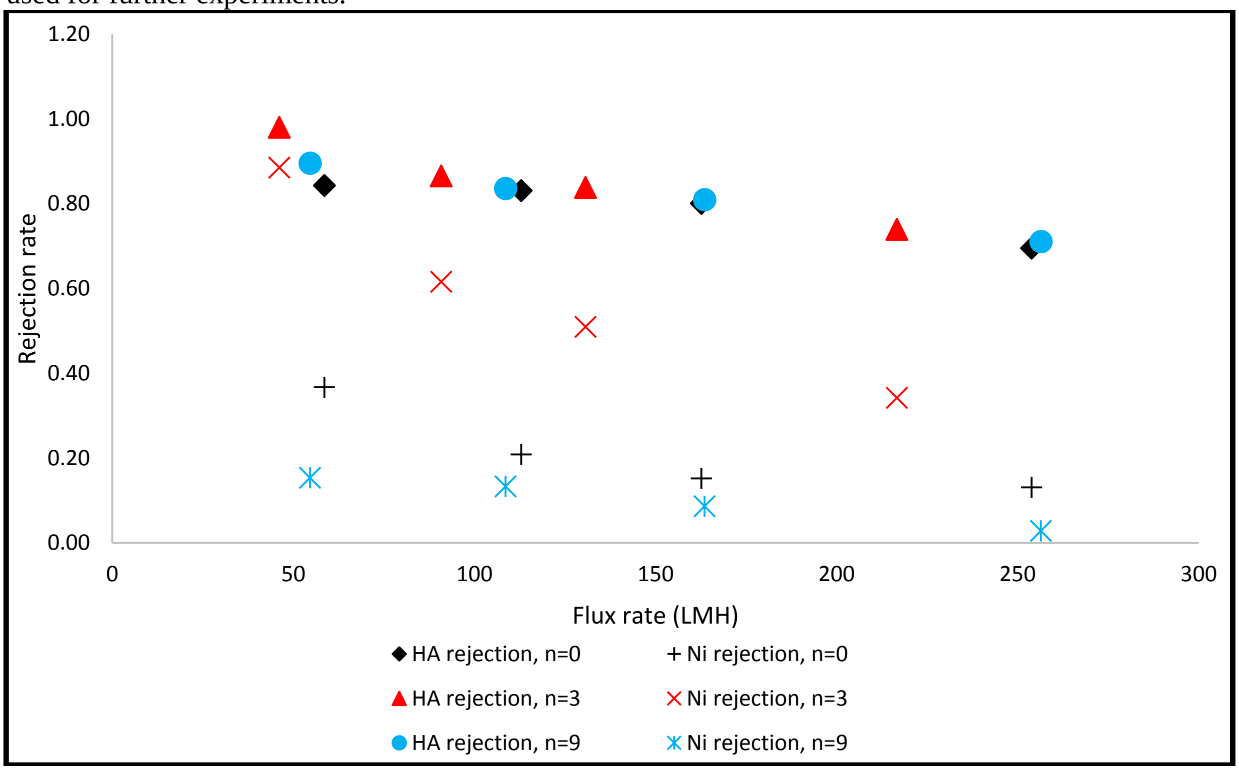

Figure 18: Comparison in rejection rates of HA and Ni using CRC 30 kD with different spacer arm lengths

4.3 Comparisons in rejection rate of HA and Ni between pure and mixture solutions

Previous studies have shown that the rejection rate of HA increases when using modified membranes; however, the feed solution for such ultrafiltration process contained only HA. Because this project was to figure out the opportunity of removing HA and Ni simultaneously when using modified membranes, it was valuable to compare the rejection rates of HA and Ni between HA solution, Ni solution, and HA-Ni solution. Figures 19 and 20 presented the comparisons in rejection rates of HA and Ni between HA, Ni, and HA-Ni solutions using unmodified CRC 30 kD membrane and CRC 30 kD membrane with spacer arm length of 3, respectively. Different feed solutions were used in this series of experiments as HA solution had concentration of 2 mg/L HA, Ni solution had concentration of 1 mg/L Ni, and HA-Ni had concentration of 2 mg/L HA + 1 mg/L Ni.

Both figures 19 and 20 showed that HA-Ni feed solution yielded lower HA rejection and higher Ni rejection than those of HA and Ni solutions when using CRC 30kD membranes. It was unclear why the rejection of HA in the HA-Ni solution was lower than that in HA solution when using unmodified CRC 30 kD membrane. Hence, more experiments should have been conducted to determine the reasons for such result. Besides that, it did make sense why the similar results appeared when using CRC 30 kD membrane with spacer arm length of 3. As heavy metal consisted of positive charges that could shield the negative charges on the surface of modified membranes, it could reduce the electrostatic interaction between negative charged membrane surface and negative charged HA substances. Therefore, the rejection of HA in the HA-Ni solution using charged membrane was lower than that in the HA solution. In contrast, the rejection of Ni in the HA-Ni solution was much higher than that in the Ni solution using membranes with different spacer arm length. Because Ni rejection was proportional to the rejection of HA in HA-Ni solution, HA rejections ranging from approximately 70% to 98% did elevate the Ni rejection.

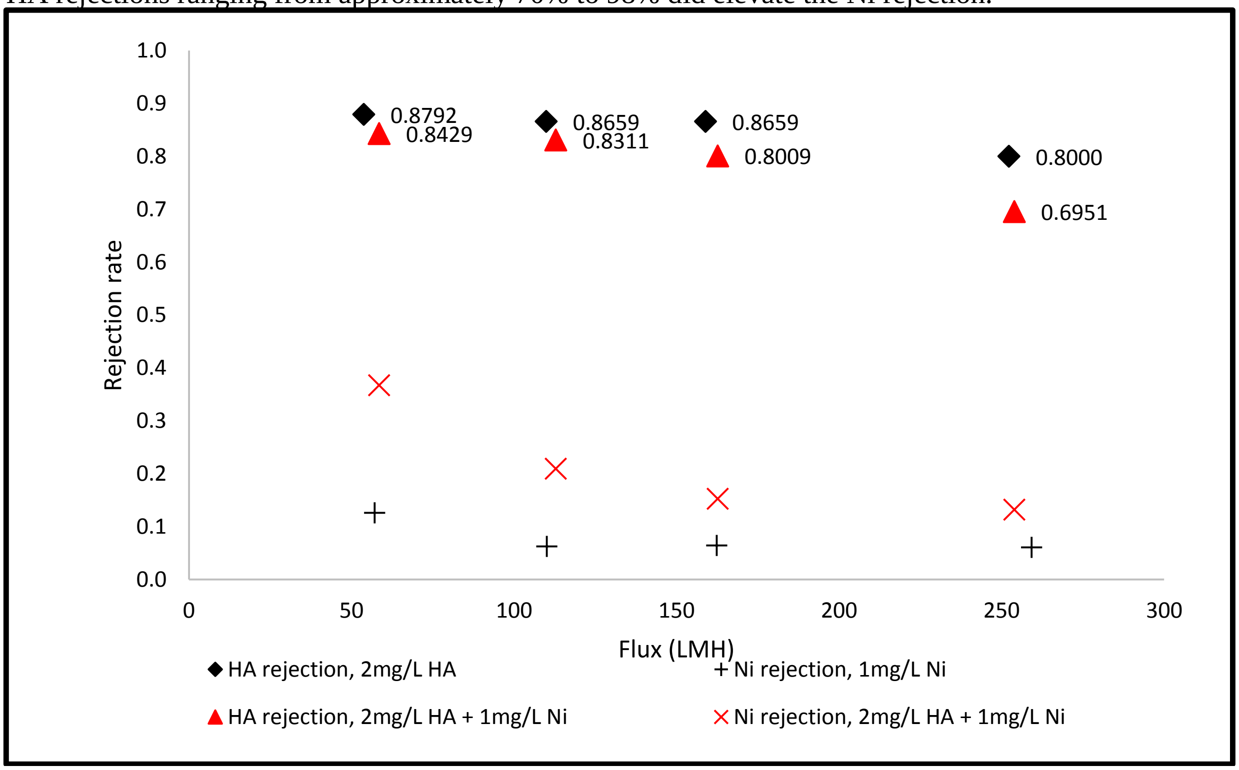

Figure 19: Comparisons in rejection rate of HA and Ni between HA and HA-Ni solutions using unmodified CRC 30kD membrane

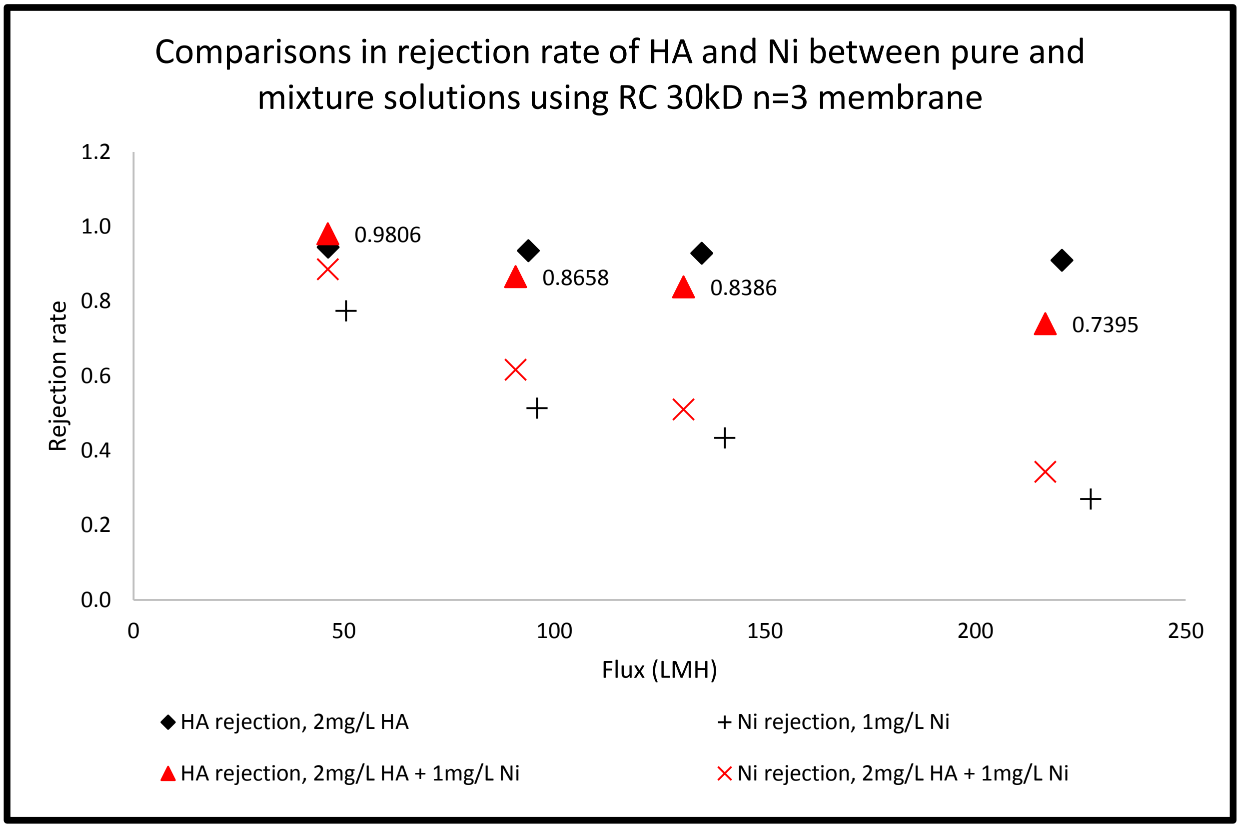

Figure 20: Comparisons in rejection rate of HA and Ni between HA and HA-Ni solutions using unmodified CRC 30kD membrane

4.4 Effect of ionic strength on rejections of HA and Ni

Since the feed solution consisted of negatively charged HA and the modified membranes also had negative charges on their surfaces, it was valuable to determine whether the rejections of HA and Ni would be improved by adding ionic strength to the feed solutions. In this case, CRC 100 kD membranes with different spacer arm lengths were used with feed solution of 2 mg/L HA and 1 mg/L Ni, pH=7. Feed solutions were changed with different ionic strength of 10 mM and 50 mM by adding calculated amount of KCl to the solution.

The rejection rates of HA and Ni with different ionic strengths using unmodified membrane, membrane with spacer arm length of 3, and membrane with spacer arm length of 9 were shown in figure 21, 22, and 23, respectively. In figure 21, the rejection rates of HA and Ni was the highest, more than 54% and 2%, respectively, when the solution ionic strength was 0 mM KCl. Rejection rates of HA and Ni reaches the lowest, approximately 9% and 0%, respectively, when the ionic strength of the solution was 50 mM KCl. Similarly for membranes with spacer arm length of 3 and 9, the rejection rates of HA and Ni attained the highest values when ionic strength of the feed solution was 0 mM KCl and the lowest values when the solution ionic strength was 50 mM KCl (figures 22 and 23).

This phenomenon could be explained based on the electrostatic forces between negative charged substances, which were HA and the negative charges on membrane surface. These forces were interrupted or shielded by the ionic strength, or KCl molecules; hence, the rejection rate of HA was reduced as the ionic strength was added, which led to the reduction in rejection rate of Ni as well.

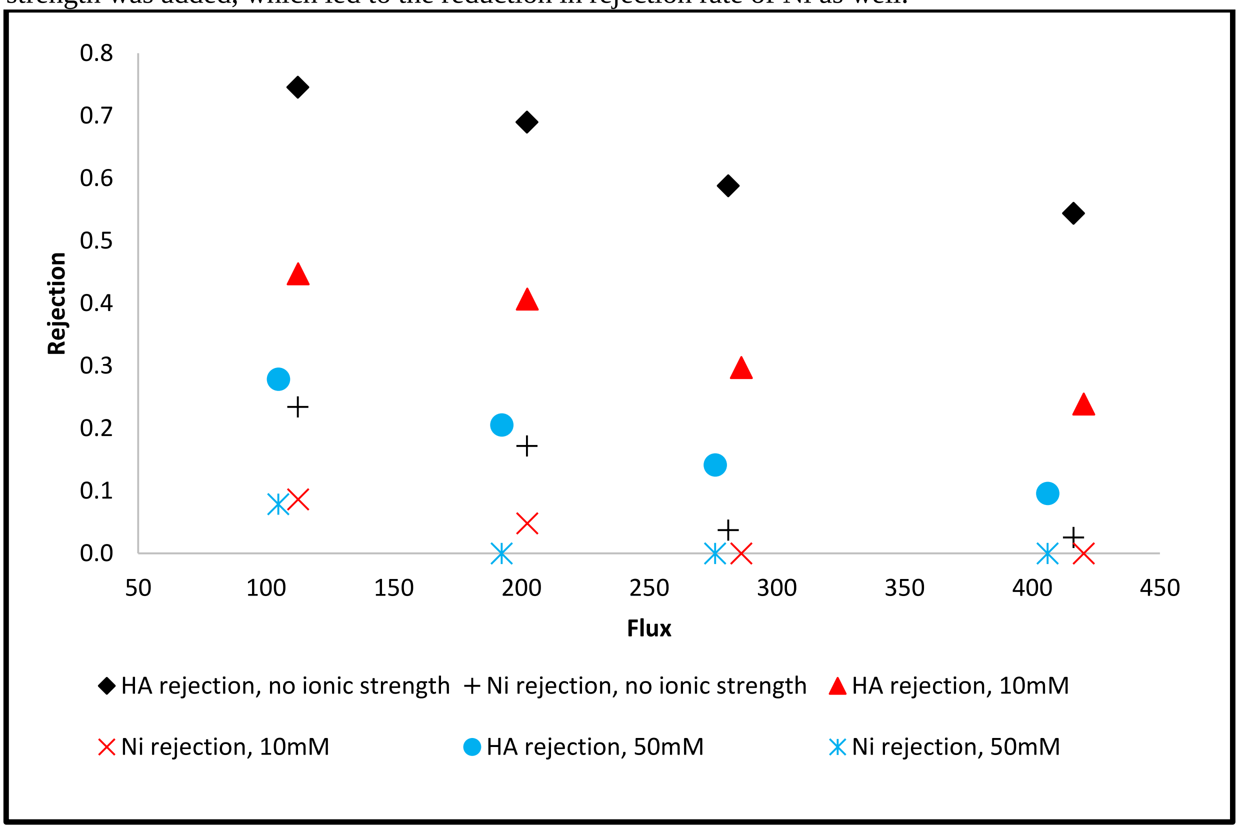

Figure 21: Rejection of HA and Ni of unmodified RC 100kD with varied ionic strength

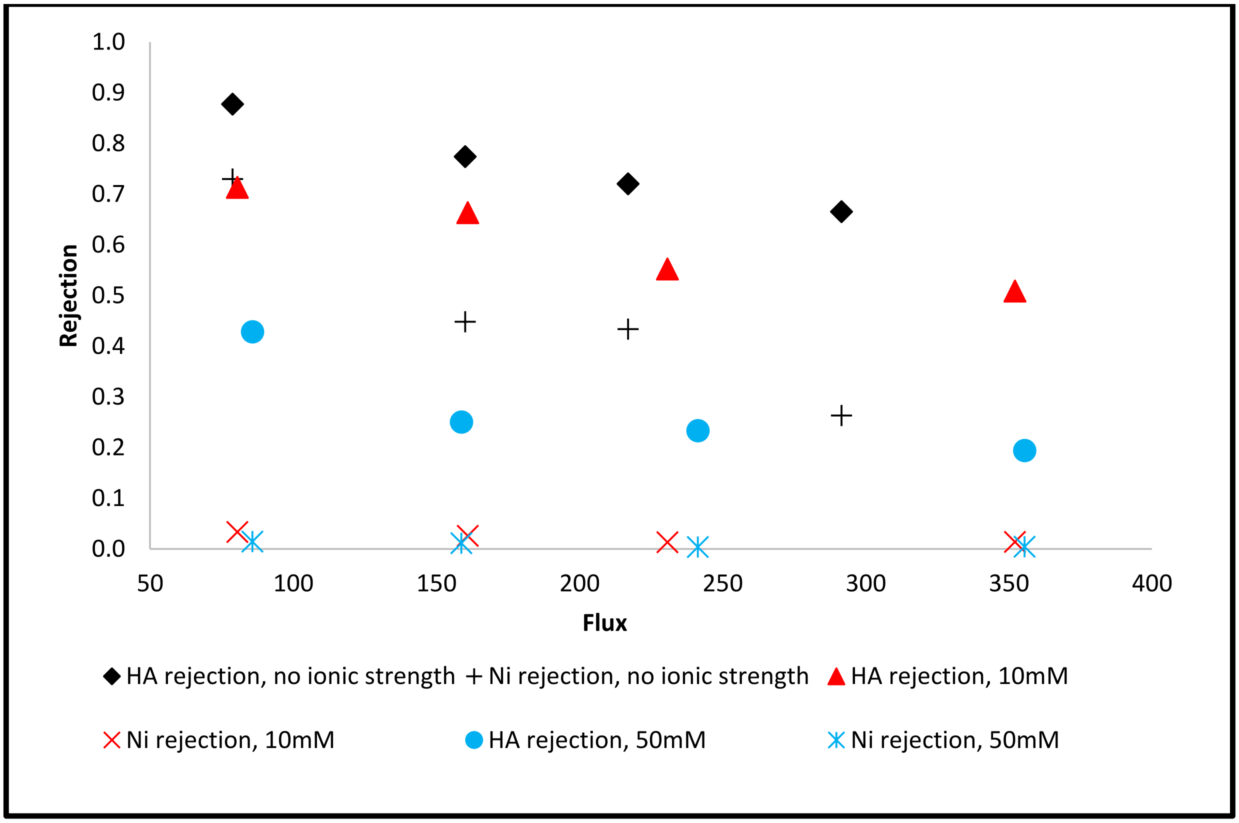

Figure 22: Rejection of HA and Ni of RC 100kD n=3 with varied ionic strength

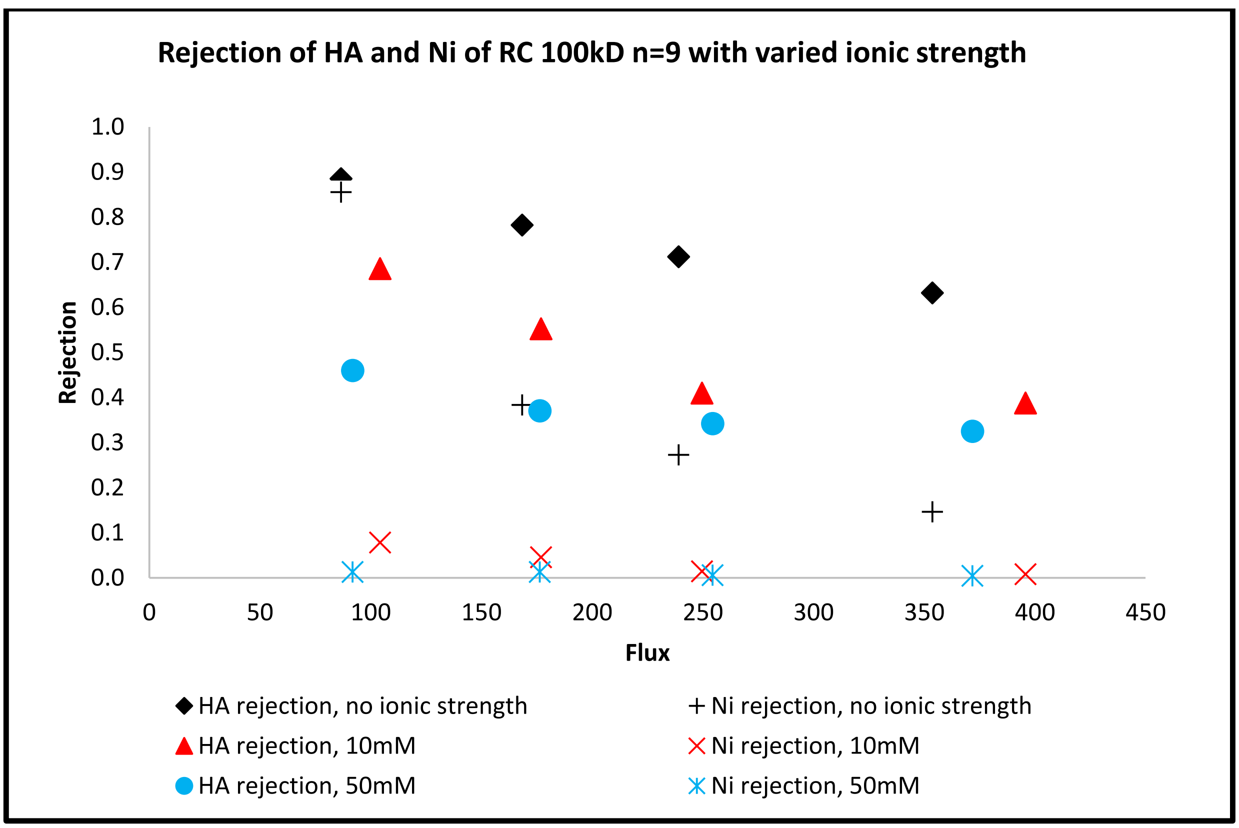

Figure 23: Rejection of HA and Ni of RC 100kD n=9 with varied ionic strength

4.5 Effect of HA-Ni ratio on rejections of HA and Ni

As previous studies have proven that the rejection rates of heavy metals in general, and Ni in particular, were directly proportional to the binding rate of heavy metal and HA, it was interesting to see how the ratio of HA and Ni in the feed solution affected the rejection rates of HA and Ni using membranes with different spacer arm lengths. Solutions with different HA:Ni ratios, which had concentrations as the following, were used.

- 8 mg/L HA + 1 mg/L Ni
- 4 mg/L HA + 1 mg/L Ni
- 2 mg/L HA + 1 mg/L Ni
- 1 mg/L HA + 1 mg/L Ni
- 2 mg/L HA + 0.5 mg/L Ni (Appendix Tables 42-44)
- 2 mg/L HA + 2 mg/L Ni (Appendix Tables 45-47)

With varied HA-Ni ratios, the rejection rates of HA and Ni using unmodified CRC 30 kD membrane and CRC 30 kD membrane with spacer arm length of 3 were presented in figures 24 and 25, respectively. It had been expected that when using the same type of membrane, rejection rates of HA would be comparable to each other although HA-Ni ratios changed. Additionally, as the HA:Ni ratio increased, the binding rates of HA and Ni were expected to increase, which incurred higher rejection rate of Ni. Figures 24 and 25 did illustrate the expected results as rejection rates of HA didn't change much with HA-Ni ratios; however, rejection rates of Ni increased as HA:Ni ratio increased. It was shown that HA:Ni ratio of 8:1, so far, yielded the highest rejection rates of HA and Ni in both unmodified and modified membranes.

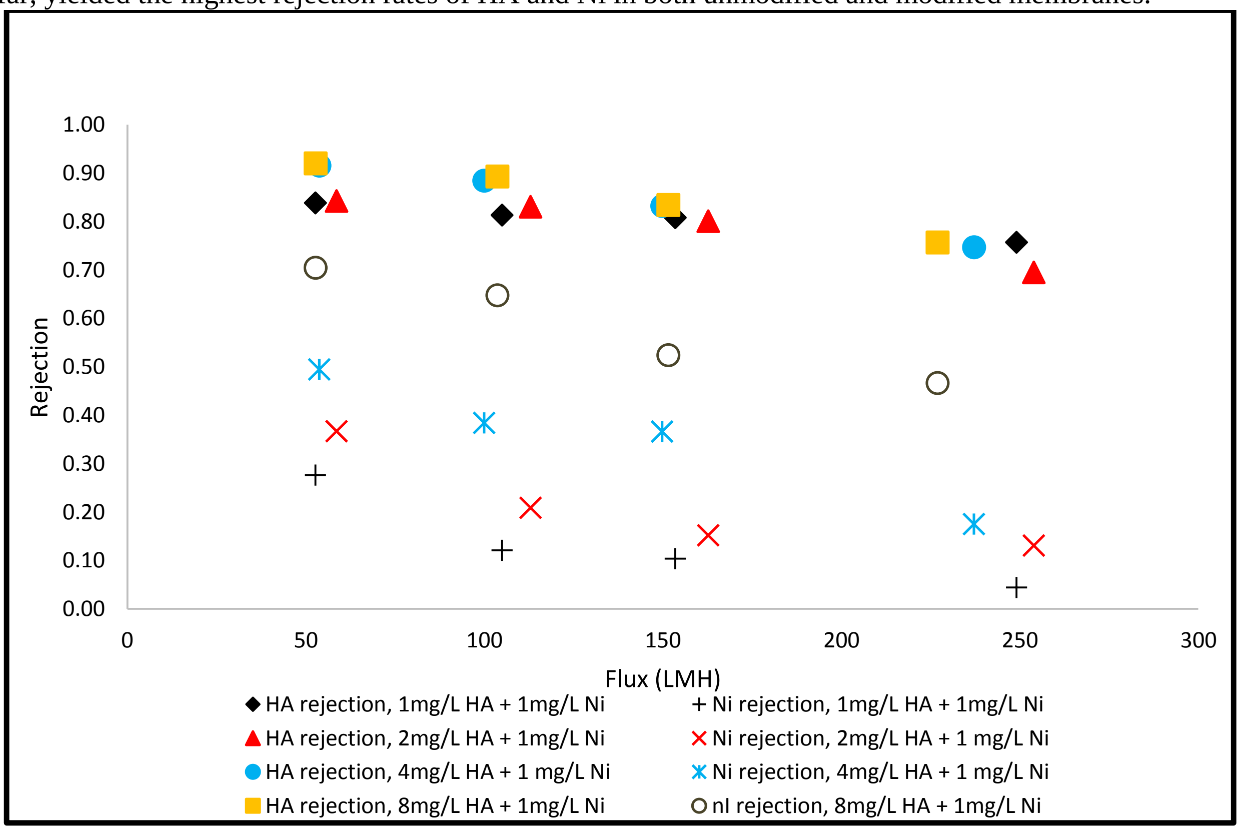

Figure 24: Rejection of HA and Ni of unmodified RC 30kD with varied HA-Ni ratio

Furthermore, with HA:Ni ratio of 8:1, the rejection rates of HA and Ni using membranes with different spacer arm lengths were compared in figure 26 to determine which membrane worked the best. It was not surprised to see that membrane with spacer arm length of 3 produced higher rejection rates of HA and Ni than unmodified membrane. The rejection rates of HA and Ni with modified membrane were found to be more than 82% and 83%, while those of unmodified membrane were more than 75% and 46%, respectively.

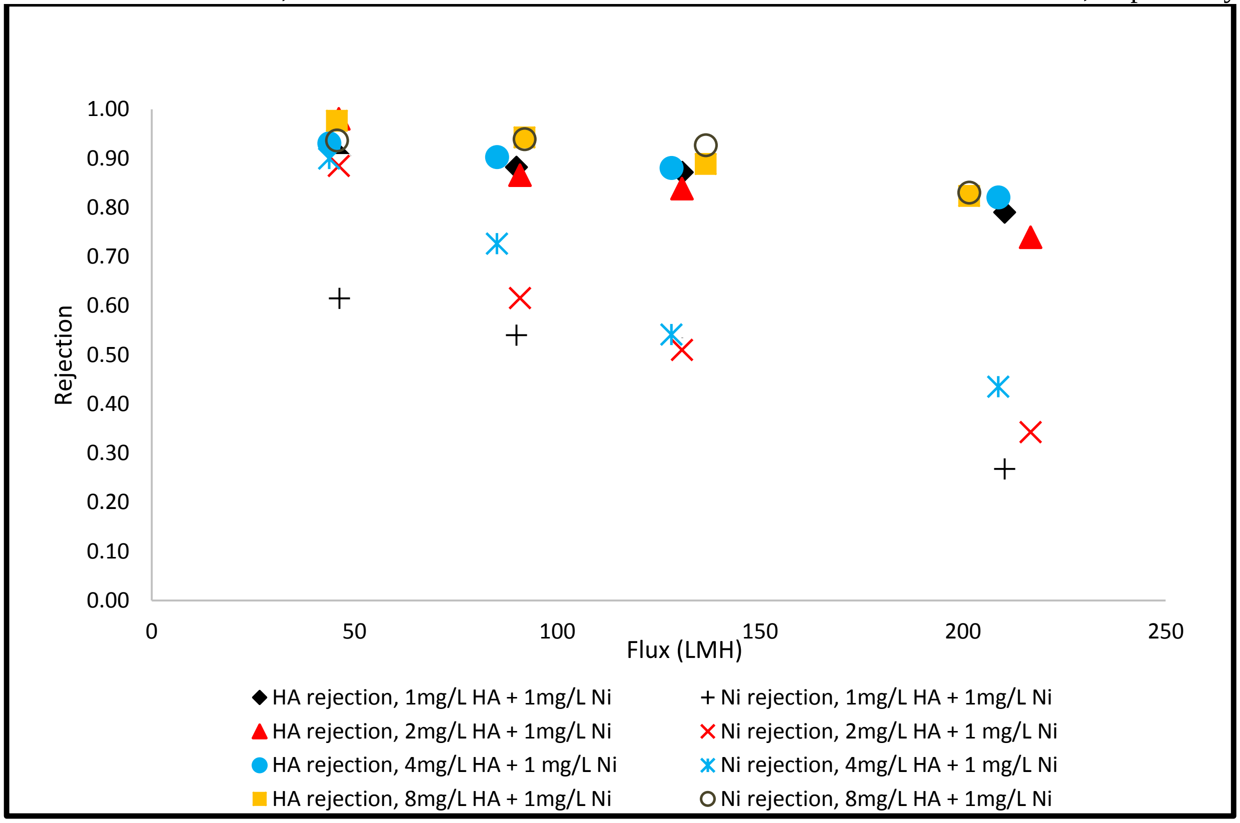

Figure 25: Rejection of HA and Ni of RC 30kD n=3 with varied HA-Ni ratio

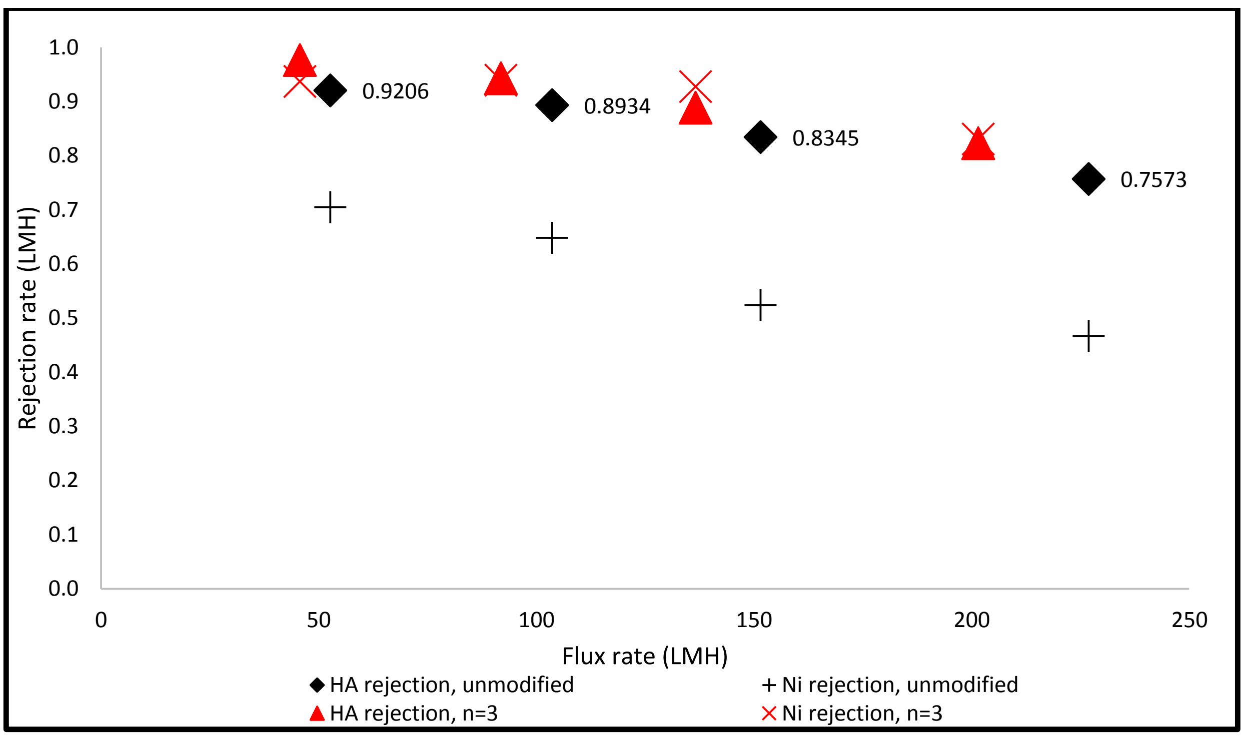

Figure 26: Rejection of HA and Ni using RC 30kD membranes with different spacer arm lengths, 8mg/L HA + 1 mg/L Ni

4.6 Effect of pH on rejection of HA and Ni

Among all the experiment results presented above, it was found that the feed solution with HA:Ni ratio of 8:1 using CRC 30 kD membrane with spacer arm length of 3 yielded the highest rejection rate of HA and Ni. Besides that, it was valuable to investigate the effect of pH to the rejection rates of HA and Ni. Hence, the experiment showing effect of pH to ultrafiltration process was conducted, and its result was displayed in figure 27.

Figure 27 presented the rejection rates of HA and Ni after ultrafiltration process with 8 mg/L HA and 1 mg/L Ni at pH 3.5 and 7.0 using membrane with spacer arm length of 3. The result showed that the rejections of HA and Ni were smaller at pH 3.5, compared to those at pH 7.0. Due to the polar characteristics of HA, the rejection of HA was dependent on the solution pH. Hence, rejection rate of HA increased with an increase in pH. Also, heavy metals were previously proven to exist as free ions in a strong acidic solution; therefore, at low pH, the molecular sizes of heavy metals were typically smaller than pore sizes of the membranes. So at pH 3.5, rejection rate of Ni decreased significantly compared to that at pH 7.0.

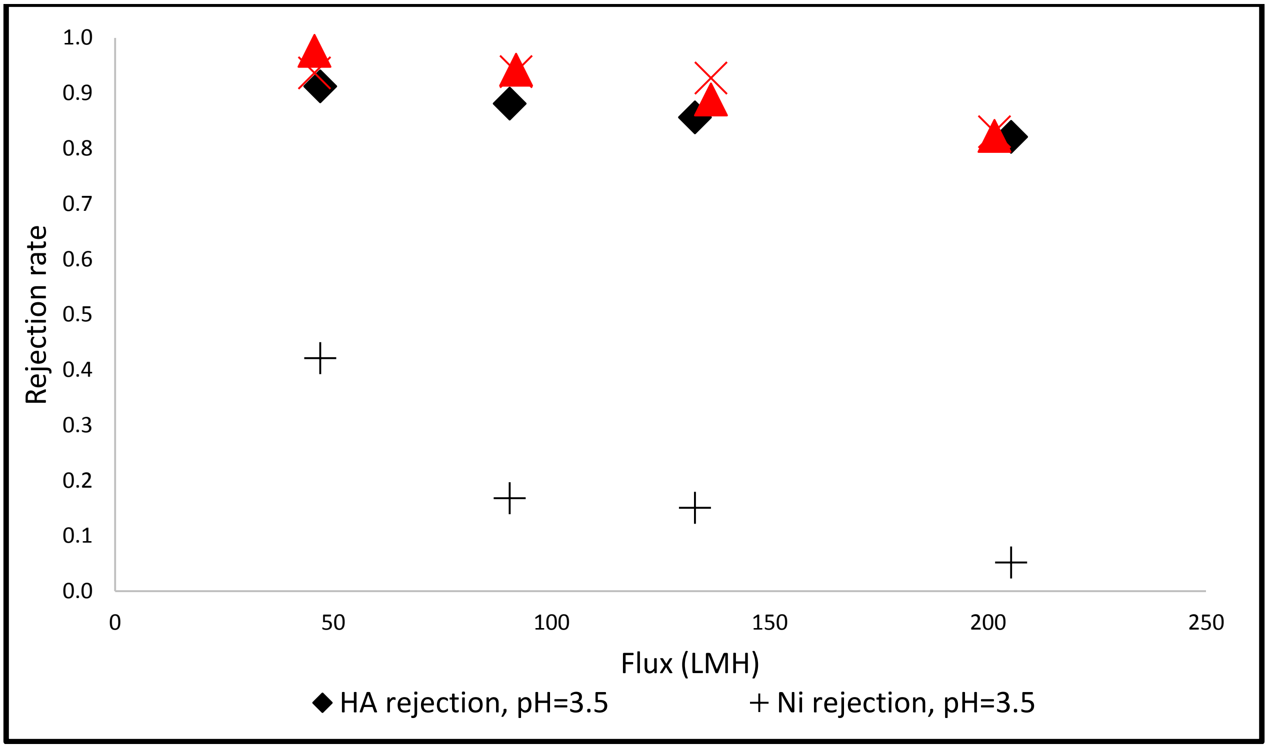

Figure 27: HA and Ni rejection using RC 30kD n=3, 8mg/L HA + 1mg/L Ni with different pH

4.7 Membrane fouling comparison

Similar to section 4.6, among all the experiments conducted so far in this project, the best condition to produce high rejection rates of HA and Ni, including HA:Ni ratio and pH of feed solution and type of membrane, was chosen to determine the membrane fouling overtime. Feed solution used in this experiment had concentration of 8 mg/L HA and 1 mg/L Ni, pH of 7. Both unmodified membrane and membrane with spacer arm length of 3 were employed in these 4-hour experiments.

Figures 28 and 29 showed the rejection rates of HA and Ni along with membrane fouling between unmodified membrane and membrane with spacer arm length of 3. It showed that the rejection rates of HA and Ni using modified membrane were relatively higher than those using unmodified membrane. Additionally, figure 29 presented that modified membrane had less flux decline compared to unmodified membrane. The phenomenon was caused by electrostatic repulsion between HA and negatively charged membrane, which led to less HA deposited on membrane surface; therefore, less flux decline was observed.

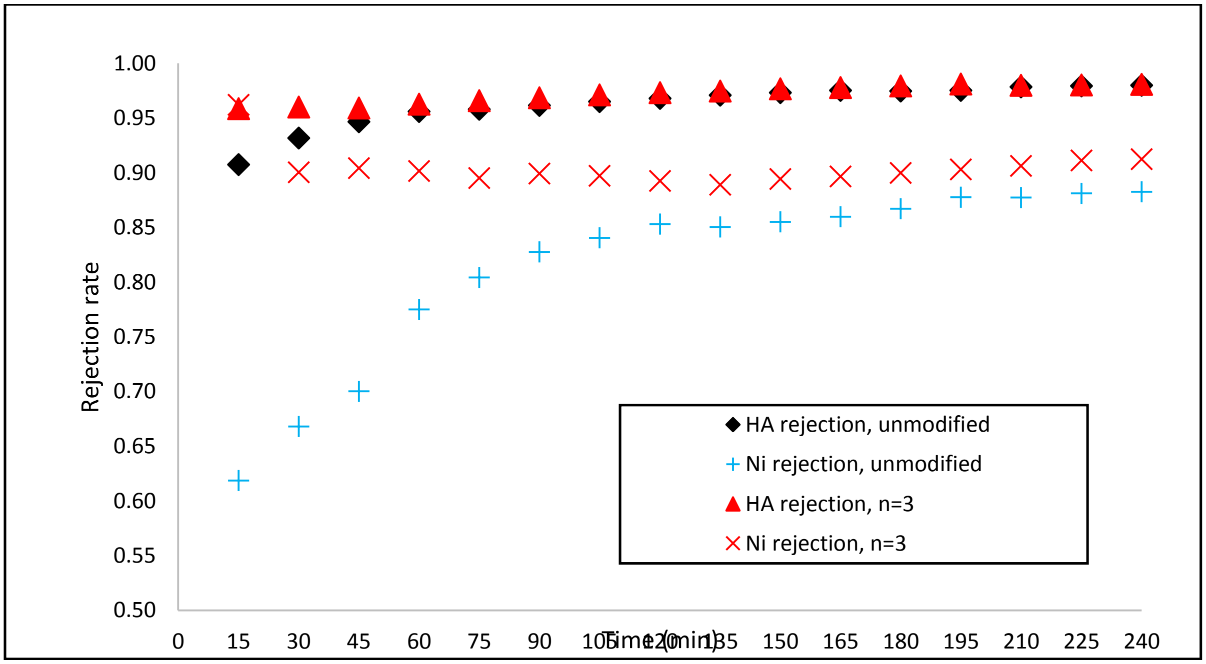

Figure 28: Rejection of HA and Ni overtime using membrane of different spacer arm length

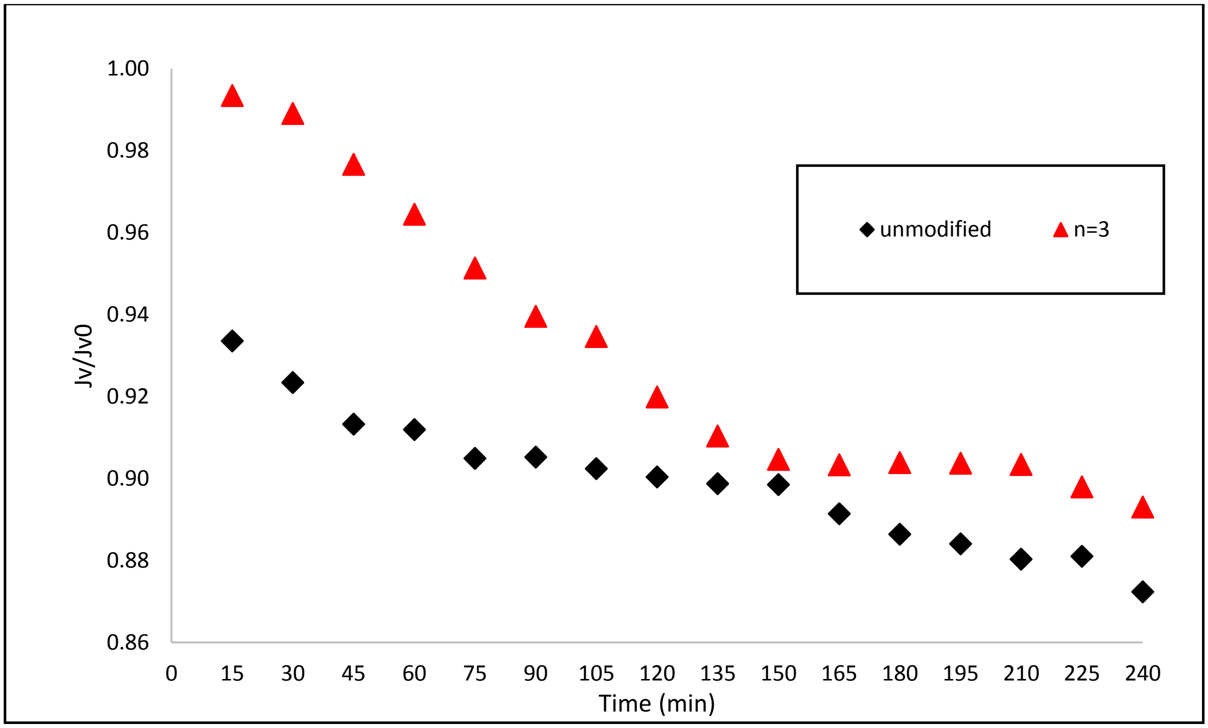

Figure 29: J_v/J_{v0} overtime using membrane of different spacer arm length

Chapter 5. Conclusion and Recommendations

In conclusion, simultaneous rejections of NOM and heavy metal using membranes with different spacer arm lengths were investigated in this project. The effects of several factors on the rejection rates of HA, a main component of NOM, and Ni, a common heavy metal were discussed, including effects of MWCO, spacer arm lengths, single-element or mixture solution, ionic strengths, HA-Ni ratios, pHs, and membrane fouling to the rejection rates of HA and Ni. After all the effects were investigated, the following conclusions and recommendations can be drawn from this project:

(1) As CRC 100 kD membrane had larger pore sizes than CRC 30 kD membrane, the rejection rates of HA and Ni using CRC 100 kD membranes were smaller than those of CRC 30 kD membranes
(2) Among different versions of membranes, membrane with spacer arm length of 3 yielded the highest rejection rates of HA and Ni. The two –step modification of membrane with spacer arm length of 9 needs to be investigated for further understanding why membrane with spacer arm length of 9 didn't yield the highest rejection rate of HA and Ni as expected from previous studies.
(3) The rejection rate of HA in HA solution was comparably higher than that in HA-Ni solution, while rejection rate of Ni in Ni solution was quite lower than that in HA-Ni solution when using either unmodified membrane or membrane with spacer arm length of 3.
(4) As ionic strength hindered the electrostatic repulsion between HA and negative charges on membrane surface, the rejection rates of HA and Ni decreased as more ionic strengths were added.
(5) Because rejection rate of heavy metal was found to increase as the binding rate between HA and heavy metal increased, HA:Ni ratio of 8:1, so far, was found to yield the highest rejection rates of HA and Ni when using membrane with spacer arm length of 3.
(6) The rejection rates of HA and Ni decreased as pH was decreased because the rejection of HA depended on pH of solution. Also, in acidic environment, heavy metal existed as ion free form which was smaller than the membrane pore size. Hence, reducing solution pH also caused a decrease in heavy metal rejection.
(7) The negative charged CRC membranes, particularly membrane with spacer arm length of 3, had higher rejection rates of HA and Ni but smaller flux decline than unmodified membrane

At this point of the project, it is recommended that more tests should be done on the membraned such as zeta potential and membrane pore size. Also, the process of modifying CRC n=9 membrane should be investigated as well as the effect of CRC n=9 membrane to simultaneous removal of HA and Ni should be observed. Furthermore, more experiments with different heavy metals should be conducted. Last but not least, sample tubes used to collect samples should be hand- washed with pure water to ensure reliable results.

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Appendix

CRC 30 kD membranes with different spacer arm lengths

Table 2: CRC 30 kD, unmodified, 2 mg/L HA, pH = 7

30kD n=0 CRC, 2mg/L HA, pH=7, no ionic strength											
		$[Abs\text{- }HA]_{initial}$	0.056			Membrane S.A		0.00049			
Pressure (Mpa)	**Samples**	**Abs HA**	**Abs_{avg} HA**	**Stir-cell HA**	**Reject coefficient HA**	**Flask**	**Flask + Sample**	**Sample (L)**	**Time (hr)**	**Jv (LMH)**	**Jv_{avg} (LMH)**
0.02	1	0.009	0.009	0.0745	0.8792	13.9401	16.6232	0.00268	0.1	54.6597	53.7660
	2					14.0446	16.6889	0.00264	0.1	53.8692	
	3					17.8788	20.4691	0.00259	0.1	52.7692	
	4	0.093									
0.04	1	0.011	0.011	0.082	0.8659	17.3882	22.7941	0.00541	0.1	110.1281	109.8843
	2					17.3313	22.6251	0.00529	0.1	107.8444	
	3					17.6357	23.1178	0.00548	0.1	111.6804	
	4	0.108									
0.06	1	0.011	0.011	0.085	0.8659	17.2438	25.1131	0.00787	0.1	160.3121	158.8881
	2	0.011				17.8342	25.6276	0.00779	0.1	158.7658	
	3	0.012				17.7882	25.5237	0.00774	0.1	157.5863	
	4	0.113									
0.1	1	0.017	0.017	0.085	0.8000	17.4780	30.2207	0.01274	0.1	259.5922	252.2291
	2	0.017				17.4865	29.4539	0.01197	0.1	243.7979	
	3	0.017				17.3717	29.8054	0.01243	0.1	253.2973	
	4	0.114									
Solution in bottle connected to stir cell		0.057									
Original solution		0.055									

Table 3: CRC 30 kD, n=3, 2 mg/L HA, pH = 7

30kD n=0 CRC, 2mg/L HA, pH=7, no ionic strength											
		$[Abs\text{- }HA]_{initial}$	0.0545			Membrane S.A		0.00049			
Pressure (Mpa)	**Samples**	**Abs HA**	**Abs_{avg} HA**	**Stir-cell HA**	**Reject coefficient HA**	**Flask**	**Flask + Sample**	**Sample (L)**	**Time (hr)**	**Jv (LMH)**	**Jv_{avg} (LMH)**
0.02	1	0.004	0.004	0.072	0.944	17.2436	19.5616	0.00232	0.1	47.2219	46.2203
	2					13.9353	16.2839	0.00235	0.1	47.8453	
	3					14.0384	16.1783	0.00214	0.1	43.5937	
	4	0.089									
0.04	1	0.005	0.005	0.077	0.935	17.2039	21.9324	0.00473	0.1	96.3282	93.7885
	2					17.4819	22.0512	0.00457	0.1	93.0850	
	3					17.4830	21.9967	0.00451	0.1	91.9523	
	4	0.100									
0.06	1	0.007	0.006	0.088	0.928	17.4218	24.2149	0.00679	0.1	138.3879	134.9960
	2	0.005				17.3758	23.9466	0.00657	0.1	133.8592	
	3	0.007				17.4883	24.0042	0.00652	0.1	132.7408	
	4	0.122									
0.1	1	0.007	0.007	0.081	0.909	17.3819	28.4184	0.01104	0.1	224.8337	220.5991
	2	0.007				17.6516	28.4630	0.01081	0.1	220.2480	
	3	0.008				17.6428	28.2808	0.01064	0.1	216.7156	
	4	0.107									
Solution in bottle connected to stir cell		0.055									
Original solution		0.054									

Table 4: CRC 30 kD, unmodified, 1 mg/L Ni, pH = 7

30kD n=0 CRC, 1mg/L Ni, pH=7, no ionic strength											
		$[Abs\text{- }Ni]_{initial}$	0.065875				Membrane S.A	0.00049			
Pressure (Mpa)	**Samples**	**Abs Ni**	**Abs_{avg} Ni**	**Stir-cell Ni**	**Reject coefficient Ni**	**Flask**	**Flask + Sample**	**Sample (L)**	**Time (hr)**	**Jv (LMH)**	**Jv_{avg} (LMH)**
0.02	1	0.058	0.058	0.066	0.126	17.3703	20.2034	0.00283	0.1	57.7154	57.1070
	2					17.2476	20.1017	0.00285	0.1	58.1432	
	3					17.4608	20.1833	0.00272	0.1	55.4623	
	4	0.066									
0.04	1	0.060	0.060	0.064	0.062	17.4364	22.9357	0.00550	0.1	112.0308	110.0806
	2					17.6322	22.9876	0.00536	0.1	109.0993	
	3					18.0662	23.4222	0.00536	0.1	109.1115	
	4	0.061									
0.06	1	0.060	0.060	0.064	0.064	17.5577	25.6622	0.00810	0.1	165.1035	162.3418
	2					17.6590	25.5568	0.00790	0.1	160.8927	
	3					18.4597	26.3642	0.00790	0.1	161.0292	
	4	0.061									
0.1	1	0.062	0.062	0.066	0.060	17.3803	30.2386	0.01286	0.1	261.9471	259.2940
	2					17.3088	30.2397	0.01293	0.1	263.4261	
	3					18.2890	30.6840	0.01240	0.1	252.5089	
	4	0.065									
Solution in bottle connected to stir cell		0.067									
Original solution		0.065									

Table 5: CRC 30 kD, n=3, 1 mg/L Ni, pH = 7

30kD n=3 CRC, 1mg/L Ni, pH=7, no ionic strength											
		$[Abs\text{- }Ni]_{initial}$	0.064695				Membrane S.A	0.00049			
Pressure (Mpa)	**Samples**	**Abs Ni**	**Abs_{avg} Ni**	**Stir-cell Ni**	**Reject coefficient Ni**	**Flask**	**Flask + Sample**	**Sample (L)**	**Time (hr)**	**Jv (LMH)**	**Jv_{avg} (LMH)**
0.02	1	0.013	0.013	0.056	0.774	17.1929	19.7439	0.00255	0.1	51.9685	50.4705
	2					17.7531	20.0236	0.00227	0.1	46.2542	
	3					17.7012	20.3121	0.00261	0.1	53.1888	
	4	0.047									
0.04	1	0.030	0.030	0.062	0.513	17.5694	22.3761	0.00481	0.1	97.9213	95.8739
	2					17.6092	22.2999	0.00469	0.1	95.5582	
	3					18.4206	23.0418	0.00462	0.1	94.1423	
	4	0.060									
0.06	1	0.039	0.039	0.069	0.434	17.2938	24.2888	0.00700	0.1	142.5010	140.4726
	2					17.7661	24.6693	0.00690	0.1	140.6308	
	3					17.5009	24.2890	0.00679	0.1	138.2860	
	4	0.073									
0.1	1	0.051	0.051	0.069	0.270	18.3890	29.7333	0.01134	0.1	231.1042	227.4502
	2					17.4694	28.6001	0.01113	0.1	226.7528	
	3					17.6451	28.6649	0.01102	0.1	224.4935	
	4	0.074									
Solution in bottle connected to stir cell		0.062									
Original solution		0.067									

Table 6: CRC 30 kD, n=9, 1 mg/L Ni, pH = 7

30kD n=9 CRC, 1mg/L Ni, pH=7, no ionic strength											
		[Abs- Ni]$_{initial}$	0.063				Membrane S.A	0.00049			
Pressure (Mpa)	Samples	Abs Ni	Abs$_{avg}$ Ni	Stir-cell Ni	Reject coefficient Ni	Flask	Flask + Sample	Sample (L)	Time (hr)	Jv (LMH)	Jv$_{avg}$ (LMH)
0.02	1	0.017	0.017	0.057	0.712	17.3698	20.1747	0.00280	0.1	57.1410	53.6064
	2					13.7121	16.3183	0.00261	0.1	53.0931	
	3					13.5958	16.0789	0.00248	0.1	50.5853	
	4	0.052									
0.04	1	0.039	0.039	0.065	0.397	18.4989	23.6134	0.00511	0.1	104.1917	101.7926
	2					13.7851	18.7834	0.00500	0.1	101.8245	
	3					14.0416	18.9190	0.00488	0.1	99.3616	
	4	0.067									
0.06	1	0.051	0.051	0.067	0.242	17.0377	24.6813	0.00764	0.1	155.7141	155.8792
	2					17.6663	25.1657	0.00750	0.1	152.7765	
	3					17.3262	25.1383	0.00781	0.1	159.1468	
	4	0.071									
0.1	1	0.056	0.056	0.066	0.160	17.4536	29.8687	0.01242	0.1	252.9183	249.0260
	2					18.2212	30.3485	0.01213	0.1	247.0553	
	3					17.7285	29.8582	0.01213	0.1	247.1042	
	4	0.069									
Solution in bottle connected to stir cell		0.062									
Original solution		0.064									

Table 7: CRC 30 kD, unmodified, 1 mg/L HA + 1 mg/L Ni, pH = 7

30kD n=0 CRC, 1mg/L HA + 1mg/L Ni, pH=7, no ionic strength															
		[Abs- HA]$_{initial}$	0.028			[Abs- Ni]$_{initial}$	0.06127				Membrane S.A	0.00049			
Pressure (Mpa)	Samples	Abs HA	Abs$_{avg}$ HA	Stir-cell HA	Reject coefficient HA	Abs Ni	Abs$_{avg}$ Ni	Stir-cell Ni	Reject coefficient Ni	Flask	Flask + Sample	Sample (L)	Time (hr)	Jv (LMH)	Jv$_{avg}$ (LMH)
0.02	1	0.007	0.007	0.044	0.839	0.04388	0.04388	0.06066	0.2766	17.6290	20.2988	0.00267	0.1	54.3887	52.6395
	2									14.0349	16.6041	0.00257	0.1	52.3393	
	3									13.9109	16.4237	0.00251	0.1	51.1903	
	4	0.059				0.06005									
0.04	1	0.007	0.007	0.038	0.813	0.05559	0.05559	0.063285	0.1216	13.9791	19.2039	0.00522	0.1	106.4388	104.8939
	2									13.7517	18.9201	0.00517	0.1	105.2898	
	3									18.0649	23.1186	0.00505	0.1	102.9531	
	4	0.047				0.0653									
0.06	1	0.008	0.008	0.040	0.808	0.05563	0.05563	0.06211	0.1043	17.4592	25.0926	0.00763	0.1	155.5063	153.4780
	2	0.007								17.5665	25.0817	0.00752	0.1	153.0984	
	3	0.008								17.3086	24.7615	0.00745	0.1	151.8292	
	4	0.052				0.06295									
0.1	1	0.011	0.011	0.044	0.758	0.0581	0.0581	0.060805	0.0445	17.3478	29.8956	0.01255	0.1	255.6217	249.0205
	2	0.010								17.4764	29.6549	0.01218	0.1	248.0984	
	3	0.011								17.7427	29.6877	0.01195	0.1	243.3415	
	4	0.060				0.06034									
Solution in bottle connected to stir cell		0.028				0.06127									
Original solution															

Table 8: CRC 30 kD, n=3, 1 mg/L HA + 1 mg/L Ni, pH = 7

30kD n=3 CRC, 1mg/L HA + 1mg/L Ni, pH=7, no ionic strength

[Abs- HA]$_{initial}$ 0.029 | [Abs- Ni]$_{initial}$ 0.06046 | Membrane S.A 0.00049

Pressure (Mpa)	Samples	Abs HA	Abs$_{avg}$ HA	Stir-cell HA	Reject coefficient HA	Abs Ni	Abs$_{avg}$ Ni	Stir-cell Ni	Reject coefficient Ni	Flask	Flask + Sample	Sample (L)	Time (hr)	Jv (LMH)	Jv$_{avg}$ (LMH)
0.02	1	0.004	0.004	0.043	0.906	0.02162	0.02162	0.05619	0.6152	13.7105	16.0593	0.00235	0.1	47.8494	46.3031
	2									17.4896	19.7822	0.00229	0.1	46.7045	
	3									13.7818	15.9591	0.00218	0.1	44.3556	
	4	0.056				0.05192									
0.04	1	0.005	0.005	0.043	0.882	0.02764	0.02764	0.06008	0.5399	12.4368	16.8946	0.00446	0.1	90.8136	89.9233
	2									13.5929	17.9550	0.00436	0.1	88.8640	
	3									17.3194	21.7418	0.00442	0.1	90.0924	
	4	0.056				0.0597									
0.06	1	0.004	0.005	0.039	0.872	0.03184	0.03184	0.065475	0.5137	17.5309	24.1054	0.00657	0.1	133.9346	130.7878
	2	0.005								17.4509	23.8563	0.00641	0.1	130.4897	
	3	0.006								18.5286	24.8088	0.00628	0.1	127.9392	
	4	0.049				0.07049									
0.1	1	0.009	0.009	0.045	0.790	0.04658	0.04658	0.0636	0.2676	17.5969	29.4110	0.01181	0.1	240.6749	210.2991
	2	0.006								17.6656	26.6211	0.00896	0.1	182.4399	
	3	0.013								17.3246	27.5241	0.01020	0.1	207.7825	
	4	0.060				0.06674									
Solution in bottle connected to stir cell		0.029				0.06046									
Original solution															

Table 9: CRC 30 kD, unmodified, 2 mg/L HA + 1 mg/L Ni, pH = 7(first trial)

30kD n=0 CRC, 2mg/L HA + 1mg/L Ni, pH=7, no ionic strength

[Abs- HA]$_{initial}$ 0.056 | [Abs- Ni]$_{initial}$ 0.066 | Membrane S.A 0.00049

Pressure (Mpa)	Samples	Abs HA	Abs$_{avg}$ HA	Stir-cell HA	Reject coefficient HA	Abs Ni	Abs$_{avg}$ Ni	Stir-cell Ni	Reject coefficient Ni	Flask	Flask + Sample	Sample (L)	Time (hr)	Jv (LMH)	Jv$_{avg}$ (LMH)
0.02	1	0.015	0.015	0.072	0.790	0.034	0.034	0.062	0.445	17.2853	20.0537	0.00277	0.1	56.3974	57.6122
	2									17.2998	20.4903	0.00319	0.1	64.9963	
	3									18.4084	20.9336	0.00253	0.1	51.4430	
	4	0.087				0.059									
0.04	1	0.012	0.015	0.079	0.813	0.052	0.052	0.071	0.273	17.0406	22.4904	0.00545	0.1	111.0224	108.8562
	2	0.016								17.7699	23.1314	0.00536	0.1	109.2236	
	3	0.016								17.7904	23.0095	0.00522	0.1	106.3226	
	4	0.101				0.077									
0.06	1	0.026	0.026	0.075	0.653	0.055	0.055	0.070	0.206	17.3947	27.8978	0.01050	0.1	213.9674	193.9045
	2	0.026								17.2394	26.2599	0.00902	0.1	183.7641	
	3	0.026								17.1485	26.1797	0.00903	0.1	183.9821	
	4	0.094				0.074									
0.1	1	0.022	0.024	0.081	0.698	0.064	0.064	0.073	0.133	18.1483	30.5840	0.01244	0.1	253.3380	246.9256
	2	0.025								18.2187	30.3986	0.01218	0.1	248.1269	
	3	0.026								18.5062	30.2534	0.01175	0.1	239.3120	
	4	0.105				0.081									
Solution in bottle connected to stir cell		0.056				0.066									
Original solution															

Table 10: CRC 30 kD, unmodified, 2 mg/L HA + 1 mg/L Ni, pH = 7(second trial)

Pressure (Mpa)	Samples	Abs HA	Abs_{avg} HA	Stir-cell HA	Reject coefficient HA	Abs Ni	Abs_{avg} Ni	Stir-cell Ni	Reject coefficient Ni	Flask	Flask + Sample	Sample (L)	Time (hr)	Jv (LMH)	Jv_{avg} (LMH)
		$[Abs\text{- }HA]_{initial}$	0.05875			$[Abs\text{- }Ni]_{initial}$	0.067				Membrane S.A	0.00049			
0.02	1	0.012	0.012	0.076	0.843	0.038	0.038	0.061	0.367	17.5345	20.4415	0.00291	0.1	59.2209	58.5364
	2									13.9029	16.8407	0.00294	0.1	59.8484	
	3									13.9395	16.7149	0.00278	0.1	56.5400	
	4	0.094				0.055									
0.04	1	0.014	0.014	0.083	0.831	0.051	0.051	0.065	0.209	18.5045	24.1738	0.00567	0.1	115.4940	112.8912
	2									17.2683	22.7704	0.00550	0.1	112.0879	
	3									17.3095	22.7627	0.00545	0.1	111.0917	
	4	0.107				0.063									
0.06	1	0.017	0.017	0.085	0.801	0.057	0.057	0.067	0.153	18.3887	26.5273	0.00814	0.1	165.7982	162.6827
	2	0.017								17.2384	25.2040	0.00797	0.1	162.2739	
	3	0.017								17.4505	25.3033	0.00785	0.1	159.9759	
	4	0.112				0.067									
0.1	1	0.027	0.026	0.086	0.695	0.059	0.059	0.068	0.131	18.0508	30.6085	0.01256	0.1	255.8234	253.9050
	2	0.025								17.4587	29.6013	0.01214	0.1	247.3670	
	3	0.027								17.7032	30.3935	0.01269	0.1	258.5247	
	4	0.114				0.069									
Solution in bottle		0.059				0.067									
Original solution		0.059													

Table 11: CRC 30 kD, n=3, 2 mg/L HA + 1 mg/L Ni, pH = 7(first trial)

30kD n=3 CRC, 2mg/L HA + 1mg/L Ni, pH=7, no ionic strength															
		$[Abs\text{- }HA]_{initial}$	0.051			$[Abs\text{- }Ni]_{initial}$	0.05793				Membrane S.A	0.00049			
Pressure (Mpa)	Samples	Abs HA	Abs_{avg} HA	Stir-cell HA	Reject coefficient HA	Abs Ni	Abs_{avg} Ni	Stir-cell Ni	Reject coefficient Ni	Flask	Flask + Sample	Sample (L)	Time (hr)	Jv (LMH)	Jv_{avg} (LMH)
0.02	1	0.010	0.010	0.081	0.877	0.001	0.001	0.066	0.979	17.5739	20.0251	0.00245	0.1	49.9354	48.8591
	2									17.2704	19.6545	0.00238	0.1	48.5685	
	3									17.1496	19.5094	0.00236	0.1	48.0735	
	4	0.111				0.074									
0.04	1	0.013	0.012	0.078	0.841	0.035	0.035	0.070	0.504	17.2853	22.2865	0.00500	0.1	101.8836	100.3856
	2	0.011								17.2839	22.0885	0.00480	0.1	97.8785	
	3	0.013								17.3086	22.2858	0.00498	0.1	101.3947	
	4	0.104				0.083									
0.06	1	0.012	0.013	0.081	0.844	0.043	0.043	0.071	0.393	17.8486	25.0400	0.00719	0.1	146.5020	140.4095
	2	0.012								17.8399	24.4055	0.00657	0.1	133.7533	
	3	0.014								17.9424	24.8624	0.00692	0.1	140.9731	
	4	0.111				0.083									
0.1	1	0.012	0.014	0.080	0.824	0.050	0.050	0.070	0.289	17.9703	29.1972	0.01123	0.1	228.7125	219.7639
	2	0.015								17.8079	28.4493	0.01064	0.1	216.7848	
	3	0.015								17.4851	27.9797	0.01049	0.1	213.7942	
	4	0.108				0.082									
Solution in bottle connected to stir cell		0.051				0.058									
Original solution															

Table 12: CRC 30 kD, n=3, 2 mg/L HA + 1 mg/L Ni, pH = 7(second trial)

		[Abs- HA]$_{initial}$	0.059			[Abs- Ni]$_{initial}$	0.06689				Membrane S.A	0.00049			
Pressure (Mpa)	Samples	Abs HA	Abs$_{avg}$ HA	Stir-cell HA	Reject coefficient HA	Abs Ni	Abs$_{avg}$ Ni	Stir-cell Ni	Reject coefficient Ni	Flask	Flask + Sample	Sample (L)	Time (hr)	Jv (LMH)	Jv$_{avg}$ (LMH)
0.02	1	0.010	0.010	0.515	0.981	0.006	0.006	0.053	0.885	12.4619	14.7165	0.00225	0.1	45.9303	46.1578
	2									13.7134	15.9607	0.00225	0.1	45.7816	
	3									17.4215	19.7169	0.00230	0.1	46.7615	
	4	0.970				0.039									
0.04	1	0.010	0.010	0.075	0.866	0.028	0.028	0.072	0.616	17.4356	21.9581	0.00452	0.1	92.1316	90.8122
	2									17.7295	22.0853	0.00436	0.1	88.7356	
	3									17.3450	21.8399	0.00449	0.1	91.5694	
	4	0.090				0.077									
0.06	1	0.012	0.013	0.080	0.839	0.037	0.037	0.075	0.510	17.5168	23.9977	0.00648	0.1	132.0278	130.7091
	2	0.014								17.5924	23.8803	0.00629	0.1	128.0960	
	3	0.013								17.6255	24.1052	0.00648	0.1	132.0034	
	4	0.100				0.083									
0.1	1	0.019	0.020	0.076	0.740	0.049	0.049	0.075	0.343	17.3278	28.1304	0.01080	0.1	220.0688	216.6646
	2	0.020								17.5629	28.1388	0.01058	0.1	215.4505	
	3	0.020								22.0882	32.6162	0.01053	0.1	214.4747	
	4	0.092				0.083									
Solution in bottle		0.059				0.067									
Original solution															

Table 13: CRC 30 kD, n=9, 2 mg/L HA + 1 mg/L Ni, pH = 7(first trial)

30kD n=9 CRC, 2mg/L HA + 1mg/L Ni, pH=7, no ionic strength															
		[Abs- HA]$_{initial}$	0.089			[Abs- Ni]$_{initial}$	0.05759				Membrane S.A	0.00049			
Pressure (Mpa)	Samples	Abs HA	Abs$_{avg}$ HA	Stir-cell HA	Reject coefficient HA	Abs Ni	Abs$_{avg}$ Ni	Stir-cell Ni	Reject coefficient Ni	Flask	Flask + Sample	Sample (L)	Time (hr)	Jv (LMH)	Jv$_{avg}$ (LMH)
0.02	1	0.012	0.012	0.094	0.872	0.020	0.020	0.059	0.669	17.5739	20.0251	0.00245	0.1	49.9354	48.8591
	2									17.2704	19.6545	0.00238	0.1	48.5685	
	3									17.1496	19.5094	0.00236	0.1	48.0735	
	4	0.099				0.061									
0.04	1	0.035	0.035	0.077	0.542	0.031	0.031	0.054	0.425	17.2853	22.2865	0.00500	0.1	101.8836	100.3856
	2									17.2839	22.0885	0.00480	0.1	97.8785	
	3									17.3086	22.2858	0.00498	0.1	101.3947	
	4	0.064				0.051									
0.06	1	0.013	0.015	0.097	0.845	0.032	0.032	0.070	0.538	17.8486	25.0400	0.00719	0.1	146.5020	140.4095
	2	0.014								17.8399	24.4055	0.00657	0.1	133.7533	
	3	0.018								17.9424	24.8624	0.00692	0.1	140.9731	
	4	0.105				0.082									
0.1	1	0.029	0.031	0.105	0.700	0.054	0.054	0.072	0.256	17.9703	29.1972	0.01123	0.1	228.7125	219.7639
	2	0.030								17.8079	28.4493	0.01064	0.1	216.7848	
	3	0.035								17.4851	27.9797	0.01049	0.1	213.7942	
	4	0.120				0.087									
Solution in bottle connected to stir cell		0.089				0.058									
Original solution															

Table 14: CRC 30 kD, n=9, 2 mg/L HA + 1 mg/L Ni, pH = 7(second trial)

Pressure (Mpa)	Samples	Abs HA	Abs_{avg} HA	Stir-cell HA	Reject coefficient HA	Abs Ni	Abs_{avg} Ni	Stir-cell Ni	Reject coefficient Ni	Flask	Flask + Sample	Sample (L)	Time (hr)	Jv (LMH)	Jv_{avg} (LMH)
		$[Abs- HA]_{initial}$	0.052			$[Abs- Ni]_{initial}$	0.058				Membrane S.A	0.00049			
	1									17.4165	20.1525	0.00274	0.1	55.7373	
0.02	2	0.007	0.007	0.067	0.896	0.053	0.053	0.063	0.154	14.0335	16.6530	0.00262	0.1	53.3640	54.5748
	3									13.7099	16.3912	0.00268	0.1	54.6230	
	4	0.082				0.068									
	1									17.2615	22.6269	0.00537	0.1	109.3030	
0.04	2	0.013	0.013	0.080	0.836	0.057	0.057	0.066	0.134	17.6282	22.9936	0.00537	0.1	109.3030	108.5622
	3									17.5497	22.8060	0.00526	0.1	107.0805	
	4	0.107				0.074									
	1	0.016								17.4328	25.2133	0.00778	0.1	158.5030	
0.06	2	0.016	0.016	0.086	0.810	0.061	0.061	0.066	0.086	17.9790	25.8017	0.00782	0.1	159.3627	163.5702
	3	0.017								17.3246	25.8091	0.00848	0.1	172.8448	
	4	0.120				0.075									
	1	0.023								18.5302	31.2746	0.01274	0.1	259.6268	
0.1	2	0.024	0.024	0.083	0.711	0.063	0.063	0.064	0.029	18.2427	30.8315	0.01259	0.1	256.4569	256.4868
	3	0.025								17.4540	29.8916	0.01244	0.1	253.3767	
	4	0.114				0.071									
Solution in bottle		0.052				0.058									
Original solution															

Table 15: CRC 30 kD, n=0, 4 mg/L HA + 1 mg/L Ni, pH = 7(first trial)

30kD n=0 CRC, 4mg/L HA + 1mg/L Ni, pH=7, no ionic strength

Pressure (Mpa)	Samples	Abs HA	Abs_{avg} HA	Stir-cell HA	Reject coefficient HA	Abs Ni	Abs_{avg} Ni	Stir-cell Ni	Reject coefficient Ni	Flask	Flask + Sample	Sample (L)	Time (hr)	Jv (LMH)	Jv_{avg} (LMH)
		$[Abs- HA]_{initial}$	0.112			$[Abs- Ni]_{initial}$	0.059				Membrane S.A	0.00049			
	1									17.6239	20.7950	0.00317	0.1	64.6011	
0.02	2	0.032	0.032	0.145	0.779	0.035	0.035	0.064	0.459	18.2415	21.4863	0.00324	0.1	66.1025	64.9909
	3									17.4713	20.6261	0.00315	0.1	64.2691	
	4	0.177				0.068									
	1	0.060								17.6723	25.3071	0.00763	0.1	155.5349	
0.04	2	0.060	0.059	0.146	0.596	0.046	0.046	0.068	0.321	17.4208	24.3947	0.00697	0.1	142.0711	143.3471
	3	0.057								17.2544	23.7553	0.00650	0.1	132.4352	
	4	0.180				0.077									
	1	0.061								17.6111	28.0245	0.01041	0.1	212.1400	
0.06	2	0.059	0.060	0.157	0.618	0.046	0.046	0.067	0.315	17.5437	26.0270	0.00848	0.1	172.8204	192.4802
	3														
	4	0.202				0.075									
	1	0.082								18.2061	38.2563	0.02005	0.1	408.4593	
0.1	2	0.079	0.079	0.157	0.495	0.056	0.056	0.070	0.194	17.5897	36.1715	0.01858	0.1	378.5453	374.5925
	3	0.076								18.0994	34.6307	0.01653	0.1	336.7729	
	4	0.201				0.080									
Solution in bottle connected to stir cell		0.119				0.059									
Original solution		0.105													

Table 16: CRC 30 kD, n=0, 4 mg/L HA + 1 mg/L Ni, pH = 7(second trial)

		$[Abs\text{- }HA]_{initial}$	0.107			$[Abs\text{- }Ni]_{initial}$	0.066				Membrane S.A	0.00049			
Pressure (Mpa)	**Samples**	**Abs HA**	**Abs_{avg} HA**	**Stir-cell HA**	**Reject coefficient HA**	**Abs Ni**	**Abs_{avg} Ni**	**Stir-cell Ni**	**Reject coefficient Ni**	**Flask**	**Flask + Sample**	**Sample (L)**	**Time (hr)**	**Jv (LMH)**	**Jv_{avg} (LMH)**
0.02	1	0.011	0.011	0.131	0.916	0.034	0.034	0.068	0.495	13.7077	16.4700	0.00276	0.1	56.2731	53.7545
	2									12.4562	15.0574	0.00260	0.1	52.9912	
	3									18.4910	21.0435	0.00255	0.1	51.9991	
	4	0.155				0.069									
0.04	1	0.017	0.017	0.148	0.885	0.043	0.043	0.070	0.385	13.9351	18.9019	0.00497	0.1	101.1828	99.9381
	2									13.8991	18.8285	0.00493	0.1	100.4209	
	3									17.2642	22.0851	0.00482	0.1	98.2106	
	4	0.189				0.074									
0.06	1	0.028	0.026	0.158	0.833	0.044	0.044	0.069	0.367	17.4497	24.8906	0.00744	0.1	151.5848	149.7880
	2	0.024								18.3262	25.5907	0.00726	0.1	147.9912	
	3	0.027								17.3657	24.5216	0.00716			
	4	0.208				0.072									
0.1	1	0.040	0.040	0.159	0.748	0.059	0.059	0.071	0.176	17.5184	29.6722	0.01215	0.1	247.5952	237.1268
	2	0.041								17.4512	29.0187	0.01157	0.1	235.6512	
	3	0.039								17.7257	28.9242	0.01120	0.1	228.1340	
	4	0.210				0.076									
Solution in bottle connected to stir cell		0.107				0.066									
Original solution		0.107													

Table 17: CRC 30 kD, n=3, 4 mg/L HA + 1 mg/L Ni, pH = 7(first trial)

30kD n=3 CRC, 4mg/L HA + 1mg/L Ni, pH=7, no ionic strength															
		$[Abs\text{- }HA]_{initial}$	0.1065			$[Abs\text{- }Ni]_{initial}$	0.06091				Membrane S.A	0.00049			
Pressure (Mpa)	**Samples**	**Abs HA**	**Abs_{avg} HA**	**Stir-cell HA**	**Reject coefficient HA**	**Abs Ni**	**Abs_{avg} Ni**	**Stir-cell Ni**	**Reject coefficient Ni**	**Flask**	**Flask + Sample**	**Sample (L)**	**Time (hr)**	**Jv (LMH)**	**Jv_{avg} (LMH)**
0.02	1	0.024	0.024	0.133	0.819	0.017	0.017	0.059	0.721	17.4048	19.7869	0.00238	0.1	48.5277	48.5277
	2									17.7262	20.1037	0.00238	0.1	48.4340	
	3									17.2002	19.5869	0.00239	0.1	48.6215	
	4	0.159				0.058									
0.04	1	0.025	0.025	0.139	0.820	0.020	0.020	0.068	0.698	17.4572	22.1480	0.00469	0.1	95.5602	91.8152
	2									18.0507	22.4856	0.00443	0.1	90.3470	
	3									17.9215	22.3167	0.00440	0.1	89.5383	
	4	0.171				0.074									
0.06	1	0.017	0.017	0.159	0.896	0.016	0.016	0.075	0.784	17.3158	23.4173	0.00610	0.1	124.2987	119.5990
	2	0.016								18.0507	23.6908	0.00564	0.1	114.8992	
	3									17.9215	23.4335	0.00551			
	4	0.211				0.090									
0.1	1	0.021	0.023	0.160	0.856	0.012	0.012	0.079	0.851	17.8727	27.3597	0.00949	0.1	193.2676	184.4676
	2	0.024								17.5643	26.5623	0.00900	0.1	183.3058	
	3	0.024								17.1437	25.8238	0.00868	0.1	176.8295	
	4	0.214				0.096									
Solution in bottle connected to stir cell		0.108				0.061									
Original solution		0.105													

Table 18: CRC 30 kD, n=3, 4 mg/L HA + 1 mg/L Ni, pH = 7(second trial)

		[Abs- HA]$_{initial}$	0.109			[Abs- Ni]$_{initial}$	0.06462				Membrane S.A	0.00049			
Pressure (Mpa)	**Samples**	**Abs HA**	**Abs$_{avg}$ HA**	**Stir-cell HA**	**Reject coefficient HA**	**Abs Ni**	**Abs$_{avg}$ Ni**	**Stir-cell Ni**	**Reject coefficient Ni**	**Flask**	**Flask + Sample**	**Sample (L)**	**Time (hr)**	**Jv (LMH)**	**Jv$_{avg}$ (LMH)**
0.02	1	0.010	0.010	0.146	0.931	0.005	0.005	0.055	0.900	14.3646	16.5853	0.00222	0.1	45.2397	43.7458
	2									14.0362	16.1138	0.00208	0.1	42.3245	
	3									17.7394	19.8832	0.00214	0.1	43.6731	
	4	0.182				0.044									
0.04	1	0.013	0.013	0.135	0.903	0.019	0.019	0.071	0.727	13.5946	17.7376	0.00414	0.1	84.4005	85.1400
	2									14.0401	18.2616	0.00422	0.1	85.9997	
	3									17.4468	21.6202	0.00417	0.1	85.0198	
	4	0.160				0.076									
0.06	1	0.021	0.019	0.157	0.881	0.035	0.035	0.077	0.541	17.4820	23.8531	0.00637	0.1	129.7910	128.1470
	2	0.017								17.6866	23.9319	0.00625	0.1	127.2282	
	3	0.018								18.5175	24.7723	0.00625	0.1	127.4217	
	4	0.205				0.089									
0.1	1	0.030	0.030	0.170	0.821	0.045	0.045	0.080	0.435	17.3141	27.7329	0.01042	0.1	212.2501	208.7379
	2	0.031								17.3063	27.5969	0.01029	0.1	209.6384	
	3	0.030								17.2191	27.2489	0.01003	0.1	204.3254	
	4	0.230				0.095									
Solution in bottle connected to stir cell		0.107													
Original solution		0.111				0.065									

Table 19: CRC 30 kD, unmodified, 8 mg/L HA + 1 mg/L Ni, pH = 7

30kD n=0 CRC, 8mg/L HA + 1mg/L Ni, pH=7, no ionic strength															
		[Abs- HA]$_{initial}$	0.209			[Abs- Ni]$_{initial}$	0.05894				Membrane S.A	0.00049			
Pressure (Mpa)	**Samples**	**Abs HA**	**Abs$_{avg}$ HA**	**Stir-cell HA**	**Reject coefficient HA**	**Abs Ni**	**Abs$_{avg}$ Ni**	**Stir-cell Ni**	**Reject coefficient Ni**	**Flask**	**Flask + Sample**	**Sample (L)**	**Time (hr)**	**Jv (LMH)**	**Jv$_{avg}$ (LMH)**
0.02	1	0.021	0.021	0.265	0.921	0.019	0.019	0.066	0.705	12.4590	15.0368	0.00258	0.1	52.5145	52.6727
	2									13.9367	16.5235	0.00259	0.1	52.6979	
	3									13.7491	16.3412	0.00259	0.1	52.8058	
	4	0.320				0.073									
0.04	1	0.029	0.031	0.294	0.893	0.027	0.027	0.076	0.648	17.3858	22.5085	0.00512	0.1	104.3588	103.6268
	2	0.030								18.2419	23.3090	0.00507	0.1	103.2261	
	3	0.035								17.8436	22.9141	0.00507	0.1	103.2954	
	4	0.379				0.094									
0.06	1	0.045	0.049	0.296	0.834	0.036	0.036	0.076	0.524	17.4349	24.8590	0.00742	0.1	151.2425	151.4999
	2	0.050								17.6656	24.9680	0.00730	0.1	148.7633	
	3	0.052								17.5931	25.1768	0.00758	0.1	154.4939	
	4	0.383				0.093									
0.1	1	0.074	0.071	0.293	0.757	0.039	0.039	0.073	0.467	17.9808	29.8342	0.01185	0.1	241.4755	226.8587
	2	0.068								17.5676	28.6190	0.01105	0.1	225.1373	
	3	0.071								17.7121	28.2150	0.01050	0.1	213.9633	
	4	0.376				0.087									
Solution in bottle connected to stir cell		0.212				0.059									
Original solution		0.206													

Table 20: CRC 30 kD, n=3, 8 mg/L HA + 1 mg/L Ni, pH = 7

30kD n=3 CRC, 8mg/L HA + 1mg/L Ni, pH=7, no ionic strength

$[Abs\text{- }HA]_{initial}$ 0.2075 | $[Abs\text{- }Ni]_{initial}$ 0.06091 | Membrane S.A 0.00049

Pressure (Mpa)	Samples	Abs HA	Abs_{avg} HA	Stir-cell HA	Reject coefficient HA	Abs Ni	Abs_{avg} Ni	Stir-cell Ni	Reject coefficient Ni	Flask	Flask + Sample	Sample (L)	Time (hr)	Jv (LMH)	Jv_{avg} (LMH)
0.02	1	0.006	0.006	0.259	0.977	0.003	0.003	0.052	0.937	13.9349	16.1532	0.00222	0.1	45.1908	45.6825
	2									13.7460	16.0352	0.00229	0.1	46.6352	
	3									17.1182	19.3380	0.00222	0.1	45.2214	
	4	0.310				0.043									
0.04	1	0.012	0.016	0.281	0.943	0.004	0.004	0.074	0.940	18.2526	22.7803	0.00453	0.1	92.2375	91.8933
	2	0.016								18.0439	22.5797	0.00454	0.1	92.4026	
	3	0.02								18.1417	22.6106	0.00447	0.1	91.0397	
	4	0.354				0.088						0.00000			
0.06	1	0.031	0.032	0.288	0.889	0.004	0.004	0.061	0.928	17.3394	24.1561	0.00682	0.1	138.8687	136.5470
	2	0.03								17.8663	24.5101	0.00664	0.1	135.3464	
	3	0.035								17.7237	24.3714	0.00665	0.1	135.4258	
	4	0.368				0.062									
0.1	1	0.059	0.054	0.304	0.823	0.010	0.010	0.061	0.831	17.4262	28.2392	0.01081	0.1	220.2806	201.5093
	2	0.051								22.3140	32.2460	0.00993	0.1	202.3330	
	3	0.051								17.6935	26.6232	0.00893	0.1	181.9144	
	4	0.4				0.061									
Solution in bottle connected to stir cell		0.209				0.06091									
Original solution		0.206													

Table 21: CRC 30 kD, n=9, 8 mg/L HA + 1 mg/L Ni, pH = 7

30kD n=9 CRC, 8mg/L HA + 1mg/L Ni, pH=7, no ionic strength

$[Abs\text{- }HA]_{initial}$ 0.337 | $[Abs\text{- }Ni]_{initial}$ 0.06662 | Membrane S.A 0.00049

Pressure (Mpa)	Samples	Abs HA	Abs_{avg} HA	Stir-cell HA	Reject coefficient HA	Abs Ni	Abs_{avg} Ni	Stir-cell Ni	Reject coefficient Ni	Flask	Flask + Sample	Sample (L)	Time (hr)	Jv (LMH)	Jv_{avg} (LMH)
0.02	1	0.023	0.023	0.333	0.931	0.045	0.045	0.073	0.390	12.4619	15.1761	0.00271	0.1	55.2932	53.8794
	2									13.7859	16.4488	0.00266	0.1	54.2482	
	3									18.5010	21.0583	0.00256	0.1	52.0969	
	4	0.329				0.080									
0.04	1	0.025	0.025	0.352	0.929	0.050	0.050	0.076	0.343	14.3646	19.6603	0.00530	0.1	107.8831	106.5712
	2									14.0423	19.3006	0.00526	0.1	107.1212	
	3									17.3347	22.4746	0.00514	0.1	104.7092	
	4	0.366				0.086						0.00000			
0.06	1	0.034	0.037	0.377	0.902	0.049	0.049	0.077	0.364	17.3506	25.1792	0.00783	0.1	159.4829	155.7073
	2	0.037								17.4549	25.0689	0.00761	0.1	155.1111	
	3	0.040								17.6352	25.1224	0.00749	0.1	152.5280	
	4	0.417				0.088									
0.1	1	0.061	0.061	0.272	0.777	0.052	0.052	0.080	0.348	18.3321	30.7839	0.01245	0.1	253.6660	244.8409
	2	0.060								17.0389	29.3583	0.01232	0.1	250.9688	
	3	0.061								17.7295	29.0141	0.01128	0.1	229.8880	
	4	0.207				0.093									
Solution in bottle connected to stir cell		0.465				0.067									
Original solution		0.209													

Table 22: CRC 30 kD, n=3, 8 mg/L HA + 1 mg/L Ni, pH = 3.5

30kD n=3 CRC, 8mg/L HA + 1mg/L Ni, pH=3.5, no ionic strength															
		[Abs- HA]$_{initial}$	0.1895			[Abs- Ni]$_{initial}$	0.07437				Membrane S.A	0.00049			
Pressure (Mpa)	**Samples**	**Abs HA**	**Abs$_{avg}$ HA**	**Stir-cell HA**	**Reject coefficient HA**	**Abs Ni**	**Abs$_{avg}$ Ni**	**Stir-cell Ni**	**Reject coefficient Ni**	**Flask**	**Flask + Sample**	**Sample (L)**	**Time (hr)**	**Jv (LMH)**	**Jv$_{avg}$ (LMH)**
0.02	1	0.019	0.019	0.218	0.913	0.042	0.042	0.073	0.421	17.3148	19.6950	0.00238	0.1	48.4890	47.0168
	2									17.5436	19.8661	0.00232	0.1	47.3136	
	3									17.2700	19.4911	0.00222	0.1	45.2479	
	4	0.246				0.071									
0.04	1	0.027	0.027	0.228	0.881	0.064	0.064	0.077	0.168	17.5182	21.8841	0.00437	0.1	88.9414	90.4020
	2									17.4164	21.9773	0.00456	0.1	92.9139	
	3									18.2387	22.6247	0.00439	0.1	89.3509	
	4	0.266				0.080						0.00000			
0.06	1	0.034	0.036	0.249	0.857	0.066	0.066	0.078	0.151	17.4582	24.2023	0.00674	0.1	137.3897	132.8705
	2	0.036								17.3661	23.8674	0.00650	0.1	132.4434	
	3	0.037								17.4059	23.7273	0.00632	0.1	128.7785	
	4	0.309				0.081									
0.1	1	0.047	0.047	0.265	0.821	0.072	0.072	0.076	0.052	17.3308	27.8571	0.01053	0.1	214.4400	205.3359
	2	0.048								18.4968	28.5402	0.01004	0.1	204.6025	
	3	0.047								17.5199	27.1884	0.00967	0.1	196.9651	
	4	0.340				0.077									
Solution in bottle connected to stir cell		0.183				0.076									
Original solution		0.196				0.073									

CRC 100 kD membranes with different spacer arm lengths

Table 23: CRC 100 kD, unmodified, 2 mg/L HA + 1 mg/L Ni, pH = 7, no ionic strength (first trial)

100kD unmodified CRC, 2mg/L HA + 1mg/L Ni, pH=7 no ionic strength															
		$[Abs\text{-}HA]_{initial}$	0.0555			$[Abs\text{-}Ni]_{initial}$	0.0727				Membrane S.A	0.00049			
Pressure (Mpa)	Samples	Abs HA	Abs_{avg} HA	Stir-cell HA	Reject coefficient HA	Abs Ni	Abs_{avg} Ni	Stir-cell Ni	Reject coefficient Ni	Flask	Flask + Sample	Sample (L)	Time (hr)	Jv (LMH)	Jv_{avg} (LMH)
0.02	1	0.046				0.059				17.6674	27.0254	0.009358	0.1	190.6396	
	2	0.042	0.041	0.078	0.473	0.059	0.058	0.076	0.231	17.1289	23.972	0.0068431	0.1	139.4065	150.1900
	3	0.035				0.058				17.2399	23.1561	0.0059162	0.1	120.5238	
	4	0.100				0.079									
0.06	1	0.047				0.072				17.7439	32.5155	0.0147716	0.1	300.9246	
	2	0.037	0.041	0.069	0.408	0.066	0.067	0.077	0.128	17.1789	31.1554	0.0139765	0.1	284.7269	288.4930
	3	0.038				0.064				17.4578	31.1938	0.013736	0.1	279.8275	
	4	0.082				0.082									
0.1	1	0.043				0.068				18.3708	38.8628	0.020492	0.1	417.4596	
	2	0.041	0.042	0.063	0.325	0.066	0.067	0.077	0.128	17.8474	33.8809	0.0160335	0.1	326.6318	394.6105
	3	0.043				0.066				17.8391	39.4248	0.0215857	0.1	439.7403	
	4	0.070				0.081									

Table 24: CRC 100 kD, unmodified, 2 mg/L HA + 1 mg/L Ni, pH = 7, no ionic strength (second trial)

		$[Abs\text{-}HA]_{initial}$	0.0585			$[Abs\text{-}Ni]_{initial}$	0.05123				Membrane S.A	0.00049			
Pressure (Mpa)	Samples	Abs HA	Abs_{avg} HA	Stir-cell HA	Reject coefficient HA	Abs Ni	Abs_{avg} Ni	Stir-cell Ni	Reject coefficient Ni	Flask	Flask + Sample	Sample (L)	Time (hr)	Jv (LMH)	Jv_{avg} (LMH)
0.02	1	0.020								17.7191	23.5552	0.00584	0.1	118.8921	
	2	0.020	0.023	0.089	0.746	0.042	0.042	0.055	0.235	18.2016	23.6393	0.00544	0.1	110.7759	112.4668
	3	0.028								17.8381	23.1264	0.00529	0.1	107.7324	
	4	0.120				0.059									
0.04	1	0.023								17.3253	27.5068	0.01018	0.1	207.4158	
	2		0.023	0.074	0.690	0.045	0.045	0.054	0.172	17.2251	27.1982	0.00997	0.1	203.1703	202.2101
	3									17.4128	27.0361	0.00962	0.1	196.0443	
	4	0.090				0.057									
0.06	1	0.031								17.6452	32.0008	0.01436	0.1	292.4499	
	2	0.032	0.032	0.078	0.588	0.054	0.054	0.056	0.037	17.3210	31.0569	0.01374	0.1	279.8255	281.0247
	3	0.033								17.4913	30.7841	0.01329	0.1	270.7987	
	4	0.097				0.061									
0.1	1	0.035								17.4510	39.0809	0.02163	0.1	440.6407	
	2	0.035	0.035	0.077	0.544	0.056	0.056	0.057	0.026	17.2462	37.6146	0.02037	0.1	414.9416	416.2088
	3	0.035								17.4785	36.7720	0.01929	0.1	393.0440	
	4	0.095				0.063									
Solution in bottle connected to stir cell		0.061				0.051									
Original solution		0.056													

Table 25: CRC 100 kD, n=3, 2 mg/L HA + 1 mg/L Ni, pH = 7, no ionic strength (first trial)

100kD n=3 CRC, 2mg/L HA + 1mg/L Ni, pH=7 no ionic strength															
		$[Abs\text{-}HA]_{initial}$	0.0645			$[Abs\text{-}Ni]_{initial}$	0.07804				Membrane S.A	0.00049			
Pressure (Mpa)	Samples	Abs HA	Abs_{avg} HA	Stir-cell HA	Reject coefficient HA	Abs Ni	Abs_{avg} Ni	Stir-cell Ni	Reject coefficient Ni	Flask	Flask + Sample	Sample (L)	Time (hr)	Jv (LMH)	Jv_{avg} (LMH)
0.02	1	0.020				0.002				17.5736	20.6565	0.00308	0.1	62.8043	
	2	0.020	0.020	0.095	0.789	0.002	0.002	0.079	0.978	17.69	20.8915	0.00320	0.1	65.2204	66.4733
	3	0.020				0.002				17.7676	21.2722	0.00350	0.1	71.3951	
	4	0.125				0.079									
0.06	1	0.047				0.034				17.6629	32.1015	0.01444	0.1	294.1407	
	2	0.038	0.042	0.077	0.456	0.035	0.039	0.078	0.494	18.1473	29.8955	0.01175	0.101	237.3544	263.3841
	3	0.041				0.048				17.4594	30.1562	0.01270	0.1	258.6571	
	4	0.090				0.078									
0.1	1	0.045				0.049				17.6685	35.2606	0.01759	0.1	358.3833	
	2	0.042	0.042	0.074	0.431	0.048	0.049	0.080	0.387	17.5903	32.2636	0.01467	0.1	298.9220	309.8501
	3	0.039				0.049				17.6356	30.9994	0.01336	0.1	272.2451	
	4	0.083				0.082									

Table 26: CRC 100 kD, n=3, 2 mg/L HA + 1 mg/L Ni, pH = 7, no ionic strength (second trial)

Pressure (Mpa)	Samples	Abs HA	Abs_{avg} HA	Stir-cell HA	Reject coefficient HA	Abs Ni	Abs_{avg} Ni	Stir-cell Ni	Reject coefficient Ni	Flask	Flask + Sample	Sample (L)	Time (hr)	Jv (LMH)	Jv_{avg} (LMH)
		$[Abs\text{- }HA]_{initial}$	0.0565			$[Abs\text{- }Ni]_{initial}$	0.06009			Membrane S.A	0.00049				
0.02	1									13.7488	17.4647	0.00372	0.1	75.6997	
	2	0.010	0.010	0.082	0.878	0.014	0.014	0.053	0.730	14.3609	18.3283	0.00397	0.1	80.8232	78.7480
	3									17.7078	21.6211	0.00391	0.1	79.7211	
	4	0.107				0.045									
0.04	1	0.015								17.5684	25.5256	0.00796	0.1	162.1027	
	2	0.019	0.018	0.080	0.774	0.038	0.038	0.069	0.449	18.2410	25.9841	0.00774	0.1	157.7411	160.0282
	3	0.020								17.2013	25.0671	0.00787	0.1	160.2408	
	4	0.103				0.077									
0.06	1	0.020								17.5924	28.4421	0.01085	0.1	221.0283	
	2	0.023	0.022	0.079	0.721	0.039	0.039	0.069	0.434	18.0480	28.1337	0.01009	0.1	205.4642	217.0334
	3	0.023								17.7251	28.7505	0.01103	0.1	224.6076	
	4	0.101				0.077									
0.1	1	0.022								17.6424	32.7968	0.01515	0.1	308.7229	
	2	0.024	0.024	0.071	0.665	0.050	0.050	0.067	0.263	17.4146	31.6012	0.01419	0.1	289.0070	291.5528
	3	0.025								22.0636	35.6573	0.01359	0.1	276.9286	
	4	0.085				0.075									
Solution in bottle connected to stir cell		0.057				0.060									
Original solution		0.056													

Table 27: CRC 100 kD, n=9, 2 mg/L HA + 1 mg/L Ni, pH = 7, no ionic strength (first trial)

100kD n=9 CRC, 2mg/L HA + 1mg/L Ni, pH=7 no ionic strength															
		$[Abs\text{- }HA]_{initial}$	0.055			$[Abs\text{- }Ni]_{initial}$	0.072095			Membrane S.A	0.00049				
Pressure (Mpa)	Samples	Abs HA	Abs_{avg} HA	Stir-cell HA	Reject coefficient HA	Abs Ni	Abs_{avg} Ni	Stir-cell Ni	Reject coefficient Ni	Flask	Flask + Sample	Sample (L)	Time (hr)	Jv (LMH)	Jv_{avg} (LMH)
0.02	1									17.8002	22.3468	0.00455	0.1	92.6226	
	2	0.019	0.019	0.096	0.8021	0.010	0.00953	0.0673775	0.8586	17.4798	21.7288	0.00425	0.1	86.5599	92.1493
	3									16.9455	21.7200	0.00477	0.1	97.2653	
	4	0.137				0.06266									
0.06	1	0.031								17.9712	31.0188	0.01305	0.1	265.8035	
	2	0.032	0.031333333	0.0645	0.5142	0.05815	0.05815	0.0804975	0.2776	17.8081	30.6729	0.01286	0.101	259.9136	259.4080
	3	0.031								17.4873	29.8822	0.01239	0.1	252.5068	
	4	0.074				0.0889									
0.1	1	0.025				0.05734				17.3196	40.0773	0.02276	0.1	463.6161	
	2	0.036	0.031333333	0.061	0.4863	0.05772	0.06089	0.0776475	0.2158	18.0084	37.4181	0.01941	0.1	395.4112	417.0698
	3	0.033				0.06761				17.3762	36.6274	0.01925	0.1	392.1822	
	4	0.067				0.0832									
Solution in bottle connected to stir cell		0.06				0.07091									
Original solution		0.05				0.07328									

Table 28: CRC 100 kD, n=9, 2 mg/L HA + 1 mg/L Ni, pH = 7, no ionic strength (second trial)

Pressure (Mpa)	Samples	Abs HA	Abs_{avg} HA	Stir-cell HA	Reject coefficient HA	Abs Ni	Abs_{avg} Ni	Stir-cell Ni	Reject coefficient Ni	Flask	Flask + Sample	Sample (L)	Time (hr)	Jv (LMH)	Jv_{avg} (LMH)
		$[Abs\text{- }HA]_{initial}$	0.0548			$[Abs\text{- }Ni]_{initial}$	0.06738			Membrane S.A	0.00049				
0.02	1									13.9088	18.1963	0.00429	0.1	87.3442	
	2	0.009	0.009	0.0784	0.8852	0.00901	0.00901	0.062085	0.8549	13.5932	17.9102	0.00432	0.1	87.9452	86.5810
	3									17.4465	21.5921	0.00415	0.1	84.4535	
	4	0.102				0.05679									
0.04	1	0.013								17.4892	26.0567	0.00857	0.1	174.5357	
	2	0.017	0.016666667	0.076	0.7818	0.04398	0.04398	0.07133	0.3834	17.6613	25.8692	0.00821	0.1	167.2100	168.4180
	3	0.02								17.4557	25.4819	0.00803	0.1	163.5084	
	4	0.098				0.07528									
0.06	1	0.021								17.2690	29.3391	0.01207	0.1	245.8901	
	2	0.021	0.021	0.073	0.7119	0.0535	0.0535	0.07354	0.2725	18.0454	29.9277	0.01188	0.1	242.0642	239.1253
	3	0.021								17.2669	28.5286	0.01126	0.1	229.4215	
	4	0.091				0.0797									
0.1	1	0.027								17.5294	35.8384	0.01831	0.1	372.9879	
	2	0.027	0.026666667	0.0724	0.6317	0.06252	0.06252	0.073215	0.1461	17.8297	35.1779	0.01735	0.1	353.4146	353.7895
	3	0.026								24.0434	40.4860	0.01644	0.1	334.9659	
	4	0.09				0.07905									
Solution in bottle connected to stir cell		0.052				0.06738									
Original solution		0.0576													

Table 29: CRC 100 kD, unmodified, 2 mg/L HA + 1 mg/L Ni, pH = 7, 10 mM KCl (first trial)

100kD n=0 CRC, 2mg/L HA + 1mg/L Ni, pH=7, 10 mM KCl															
		$[Abs\text{- }HA]_{initial}$	0.069			$[Abs\text{- }Ni]_{initial}$	0.078				Membrane S.A	0.00049			
Pressure (Mpa)	Samples	Abs HA	Abs_{avg} HA	Stir-cell HA	Reject coefficient HA	Abs Ni	Abs_{avg} Ni	Stir-cell Ni	Reject coefficient Ni	Flask	Flask + Sample	Sample (L)	Time (hr)	Jv (LMH)	Jv_{avg} (LMH)
0.02	1									17.3382	22.4085	0.00507	0.1	103.2913	
	2	0.053	0.053	0.071	0.248	0.072	0.072	0.074	0.027	17.3083	22.2283	0.00492	0.1	100.2294	101.0803
	3									17.3602	22.2552	0.00490	0.1	99.7201	
	4	0.072				0.071									
0.06	1	0.052				0.073				17.3207	32.6803	0.01536	0.1	312.9032	
	2	0.049	0.051	0.064	0.203	0.078	0.075	0.077	0.019	17.2711	32.4505	0.01518	0.101	306.6776	305.0339
	3	0.052								17.2899	31.7963	0.01451	0.1	295.5220	
	4	0.059				0.075									
0.1	1	0.052				0.073				18.4862	43.9318	0.02545	0.1	518.3735	
	2	0.050	0.052	0.065	0.199	0.075	0.075	0.077	0.023	18.3034	40.3007	0.02200	0.1	448.1253	465.5976
	3	0.053				0.078				17.3750	38.4970	0.02112	0.1	430.2939	
	4	0.060				0.076									
Solution in bottle connected to stir cell		0.069				0.078									
Original solution															

Table 30: CRC 100 kD, unmodified, 2 mg/L HA + 1 mg/L Ni, pH = 7, 10 mM KCl (second trial)

		$[Abs\text{- }HA]_{initial}$	0.05575			$[Abs\text{- }Ni]_{initial}$	0.07				Membrane S.A	0.00049			
Pressure (Mpa)	Samples	Abs HA	Abs_{avg} HA	Stir-cell HA	Reject coefficient HA	Abs Ni	Abs_{avg} Ni	Stir-cell Ni	Reject coefficient Ni	Flask	Flask + Sample	Sample (L)	Time (hr)	Jv (LMH)	Jv_{avg} (LMH)
0.02	1									17.3220	23.1445	0.00582	0.1	118.6150	
	2	0.040	0.040	0.072	0.447	0.064	0.064	0.070	0.086	17.3645	22.7137	0.00535	0.1	108.9730	112.5686
	3									18.0233	23.4287	0.00541	0.1	110.1179	
	4	0.089				0.070									
0.04	1	0.044								17.5247	27.5053	0.00998	0.1	203.3231	
	2	0.045	0.045	0.076	0.407	0.068	0.068	0.071	0.048	17.5465	27.8871	0.01034	0.1	210.6570	202.2706
	3	0.046								17.4014	26.8670	0.00947	0.1	192.8316	
	4	0.096				0.072									
0.06	1	0.047								17.9602	32.7222	0.01476	0.1	300.7290	
	2	0.047	0.047	0.067	0.297	0.071	0.071	0.071	0.000	17.2422	31.0340	0.01379	0.1	280.9642	286.1917
	3	0.047								17.6131	31.2045	0.01359	0.1	276.8817	
	4	0.078				0.071									
0.1	1	0.047								17.0147	38.5351	0.02152	0.1	438.4100	
	2	0.046	0.046	0.061	0.239	0.071	0.071	0.071	0.000	17.2562	37.8389	0.02058	0.1	419.3073	420.2471
	3	0.046								22.2906	42.0740	0.01978	0.1	403.0241	
	4	0.066				0.072									
Solution in bottle		0.057				0.070									
Original solution		0.0545													

Table 31: CRC 100 kD, n=3, 2 mg/L HA + 1 mg/L Ni, pH = 7, 10 mM KCl (first trial)

100kD n=3 CRC, 2mg/L HA + 1mg/L Ni, pH=7, 10 mM KCl															
		$[Abs\text{- }HA]_{initial}$	0.053			$[Abs\text{- }Ni]_{initial}$	0.07837				Membrane S.A	0.00049			
Pressure (Mpa)	Samples	Abs HA	Abs_{avg} HA	Stir-cell HA	Reject coefficient HA	Abs Ni	Abs_{avg} Ni	Stir-cell Ni	Reject coefficient Ni	Flask	Flask + Sample	Sample (L)	Time (hr)	Jv (LMH)	Jv_{avg} (LMH)
0.02	1									17.6671	22.7076	0.00504	0.1	102.6842	
	2	0.029	0.029	0.069	0.580	0.062	0.062	0.079	0.221	17.1246	21.2020	0.00408	0.1	83.0641	88.7709
	3									17.2391	21.1938	0.00395	0.1	80.5645	
	4	0.085				0.080									
0.06	1	0.031								17.4489	31.2885	0.01384	0.1	281.9380	
	2	0.025	0.028	0.077	0.638	0.075	0.075	0.081	0.070	17.1731	28.1522	0.01098	0.101	221.8159	239.0374
	3	0.027								17.4950	27.9682	0.01047	0.1	213.3583	
	4	0.100				0.083									
0.1	1	0.031				0.078				17.5236	33.8946	0.01637	0.1	333.5073	
	2	0.033	0.033	0.080	0.581		0.076	0.082	0.069	17.2209	31.9848	0.01476	0.1	300.7677	309.4672
	3	0.036				0.074				17.5532	31.9911	0.01444	0.1	294.1265	
	4	0.106				0.086									
Solution in bottle connected to stir cell		0.054				0.078									
Original solution		0.052													

Table 32: CRC 100 kD, n=3, 2 mg/L HA + 1 mg/L Ni, pH = 7, 10 mM KCl (second trial)

		[Abs- HA]$_{initial}$	0.073			[Abs- Ni]$_{initial}$	0.07925				Membrane S.A	0.00049			
Pressure (Mpa)	**Samples**	**Abs HA**	**Abs$_{avg}$ HA**	**Stir-cell HA**	**Reject coefficient HA**	**Abs Ni**	**Abs$_{avg}$ Ni**	**Stir-cell Ni**	**Reject coefficient Ni**	**Flask**	**Flask + Sample**	**Sample (L)**	**Time (hr)**	**Jv (LMH)**	**Jv$_{avg}$ (LMH)**
0.02	1	0.029	0.029	0.087	0.667	0.065	0.065	0.077	0.147	17.5458	21.8442	0.00430	0.1	87.5663	83.9659
	2									17.7407	21.8662	0.00413	0.1	84.0440	
	3									17.1743	21.1154	0.00394	0.1	80.2874	
	4	0.101				0.074									
0.04	1	0.034	0.038	0.082	0.537	0.077	0.077	0.080	0.035	18.4188	26.2370	0.00782	0.1	159.2711	155.7372
	2	0.039								17.9398	25.4864	0.00755	0.1	153.7381	
	3	0.041								17.7974	25.3668	0.00757	0.1	154.2026	
	4	0.091				0.081									
0.06	1	0.043	0.047	0.067	0.299	0.079	0.079	0.080	0.019	16.9443	28.4834	0.01154	0.1	235.0726	228.8762
	2	0.047								17.2765	28.5533	0.01128	0.1	229.7291	
	3	0.051								17.8076	28.6965	0.01089	0.1	221.8268	
	4	0.061				0.081									
0.1	1	0.052	0.050	0.073	0.310	0.082	0.082	0.080	0.000	17.3202	34.3306	0.01701	0.1	346.5330	336.1780
	2	0.048								18.0076	34.6099	0.01660	0.1	338.2193	
	3	0.050								17.3762	33.2698	0.01589	0.1	323.7818	
	4	0.072				0.082									
Solution in bottle connected to stir cell		0.092				0.079									
Original solution		0.054													

Table 33: CRC 100 kD, n=3, 2 mg/L HA + 1 mg/L Ni, pH = 7, 10 mM KCl (third trial)

		[Abs- HA]$_{initial}$	0.0585			[Abs- Ni]$_{initial}$	0.06681				Membrane S.A	0.00049			
Pressure (Mpa)	**Samples**	**Abs HA**	**Abs$_{avg}$ HA**	**Stir-cell HA**	**Reject coefficient HA**	**Abs Ni**	**Abs$_{avg}$ Ni**	**Stir-cell Ni**	**Reject coefficient Ni**	**Flask**	**Flask + Sample**	**Sample (L)**	**Time (hr)**	**Jv (LMH)**	**Jv$_{avg}$ (LMH)**
0.02	1	0.021	0.021	0.073	0.713	0.067	0.067	0.069	0.034	17.4651	21.7732	0.00431	0.1	87.7639	80.5095
	2									17.5058	21.5053	0.00400	0.1	81.4771	
	3									17.6518	21.2002	0.00355	0.1	72.2874	
	4	0.088				0.071									
0.04	1	0.025	0.027	0.079	0.664	0.068	0.068	0.070	0.026	17.3853	25.4889	0.00810	0.1	165.0852	160.9667
	2	0.027								17.6604	25.5310	0.00787	0.1	160.3385	
	3	0.028								17.6466	25.3767	0.00773	0.1	157.4763	
	4	0.100				0.073									
0.06	1	0.033	0.035	0.078	0.553	0.070	0.070	0.071	0.014	17.5422	29.3473	0.01181	0.1	240.4915	230.6920
	2	0.035								18.3427	29.4790	0.01114	0.1	226.8668	
	3	0.037								17.4276	28.4584	0.01103	0.1	224.7176	
	4	0.098				0.075									
0.1	1	0.038	0.040	0.081	0.509	0.070	0.070	0.071	0.014	18.0766	35.9238	0.01785	0.1	363.5802	352.1930
	2	0.040								18.4714	35.7065	0.01724	0.1	351.1106	
	3	0.041								17.7006	34.4830	0.01678	0.1	341.8882	
	4	0.103				0.075									
Solution in bottle		0.060				0.067									
Original solution		0.057													

Table 34: CRC 100 kD, n=9, 2 mg/L HA + 1 mg/L Ni, pH = 7, 10 mM KCl

100kD n=9 CRC, 2mg/L HA + 1mg/L Ni, pH=7, 10 mM KCl															
		$[Abs\text{- }HA]_{initial}$	0.059			$[Abs\text{- }Ni]_{initial}$	0.07759				Membrane S.A	0.00049			
Pressure (Mpa)	Samples	Abs HA	Abs_{avg} HA	Stir-cell HA	Reject coefficient HA	Abs Ni	Abs_{avg} Ni	Stir-cell Ni	Reject coefficient Ni	Flask	Flask + Sample	Sample (L)	Time (hr)	Jv (LMH)	Jv_{avg} (LMH)
0.02	1	0.028	0.028	0.089	0.685	0.073	0.073	0.079	0.078	17.6135	24.1190	0.00651	0.1	132.5290	104.2040
	2									17.6560	21.5932	0.00394	0.1	80.2080	
	3									17.3382	22.2408	0.00490	0.1	99.8749	
	4	0.119				0.081									
0.04	1		0.039	0.086	0.552	0.076	0.076	0.080	0.046			0.00000	0.1	0.0000	176.9187
	2											0.00000	0.101	0.0000	
	3											0.00000	0.1	0.0000	
	4	0.113				0.082									
0.06	1	0.046	0.049	0.083	0.410	0.080	0.080	0.081	0.014	17.4789	30.4141	0.01294	0.1	263.5137	249.6335
	2	0.053								17.8045	30.0053	0.01220	0.101	246.4985	
	3	0.048								17.5752	29.3016	0.01173	0.1	238.8883	
	4	0.107				0.084									
0.1	1	0.053	0.053	0.086	0.388	0.078	0.079	0.079	0.007	17.7398	38.6436	0.02090	0.1	425.8487	395.7683
	2	0.052				0.079				17.7356	36.8638	0.01913	0.1	389.6765	
	3	0.053				0.080				17.6880	35.9377	0.01825	0.1	371.7798	
	4	0.113				0.081									
Solution in bottle connected to stir cell		0.052				0.075									
Original solution		0.066				0.081									

Table 35: CRC 100 kD, unmodified, 2 mg/L HA + 1 mg/L Ni, pH = 7, 50 mM KCl (first trial)

100kD n=0 CRC, 2mg/L HA + 1mg/L Ni, pH=7, 50 mM KCl															
		$[Abs\text{- }HA]_{initial}$	0.091			$[Abs\text{- }Ni]_{initial}$	0.08373				Membrane S.A	0.00049			
Pressure (Mpa)	Samples	Abs HA	Abs_{avg} HA	Stir-cell HA	Reject coefficient HA	Abs Ni	Abs_{avg} Ni	Stir-cell Ni	Reject coefficient Ni	Flask	Flask + Sample	Sample (L)	Time (hr)	Jv (LMH)	Jv_{avg} (LMH)
0.02	1	0.048	0.048	0.080	0.400	0.075	0.075	0.084	0.100	17.5377	22.8378	0.00530	0.1	107.9728	101.3227
	2									17.6912	22.5643	0.00487	0.1	99.2740	
	3									17.7379	22.4857	0.00475	0.1	96.7214	
	4	0.069													
0.04	1	0.049	0.047	0.073	0.347	0.080	0.080	0.082	0.027	17.6633	27.6175	0.00995	0.1	202.7853	194.5734
	2	0.046								17.4588	27.0027	0.00954	0.1	194.4267	
	3	0.047								17.7721	26.9273	0.00916	0.1	186.5082	
	4	0.054				0.080									
0.06	1	0.048	0.049	0.076	0.351	0.081	0.081	0.082	0.020	17.6684	31.1890	0.01352	0.1	275.4394	268.8892
	2	0.051								17.5905	30.6893	0.01310	0.1	266.8466	
	3	0.049								17.6359	30.6137	0.01298	0.1	264.3816	
	4	0.061				0.081									
0.1	1	0.046	0.046	0.076	0.386	0.082	0.082	0.082	0.000	18.1893	38.5207	0.02033	0.1	414.1879	398.3977
	2	0.048								17.8085	37.4525	0.01964	0.1	400.1843	
	3	0.045								18.2170	36.9105	0.01869	0.1	380.8209	
	4	0.060				0.080									
Solution in bottle connected to stir cell		0.091				0.084									
Original solution															

Table 36: CRC 100 kD, unmodified, 2 mg/L HA + 1 mg/L Ni, pH = 7, 50 mM KCl (second trial)

		$[Abs\text{- }HA]_{initial}$	0.0555			$[Abs\text{- }Ni]_{initial}$	0.0769				Membrane S.A	0.00049			
Pressure (Mpa)	**Samples**	**Abs HA**	**Abs_{avg} HA**	**Stir-cell HA**	**Reject coefficient HA**	**Abs Ni**	**Abs_{avg} Ni**	**Stir-cell Ni**	**Reject coefficient Ni**	**Flask**	**Flask + Sample**	**Sample (L)**	**Time (hr)**	**Jv (LMH)**	**Jv_{avg} (LMH)**
0.02	1									17.8300	23.1649	0.00533	0.1	108.6817	104.8416
	2	0.042	0.042	0.05825	0.2790	0.07184	0.07184	0.07798	0.0787	17.4360	22.3923	0.00496	0.1	100.9689	
	3									17.3554	22.5034	0.00515	0.1	104.8742	
	4	0.061				0.07906									
0.04	1	0.046								17.2780	27.0532	0.00978	0.1	199.1387	192.3590
	2	0.047	0.046666667	0.059	0.2057	0.0801	0.0801	0.076145	0.0000	17.1903	26.4965	0.00931	0.1	189.5843	
	3	0.047								17.2013	26.4471	0.00925	0.1	188.3539	
	4	0.062				0.07539									
0.06	1	0.047								17.4209	31.3656	0.01394	0.1	284.0791	275.8903
	2	0.047	0.047	0.055	0.1416	0.07731	0.07731	0.076205	0.0000	17.5083	31.0828	0.01357	0.1	276.5374	
	3	0.047								17.6163	30.7253	0.01311	0.1	267.0544	
	4	0.054				0.07551									
0.1	1	0.048								17.8126	38.8623	0.02105	0.1	428.8210	406.0463
	2	0.048	0.047666667	0.05275	0.0964	0.08555	0.08555	0.075495	0.0000	17.8195	37.7913	0.01997	0.1	406.8622	
	3	0.047								17.4478	32.5711	0.01512	0.081	382.4557	
	4	0.05				0.07409									
Solution in bottle connected to stir cell		0.057				0.0769									
Original solution		0.054													

Table 37: CRC 100 kD, n=3, 2 mg/L HA + 1 mg/L Ni, pH = 7, 50 mM KCl (first trial)

100kD n=3 CRC, 2mg/L HA + 1mg/L Ni, pH=7, 50 mM KCl															
		$[Abs\text{- }HA]_{initial}$	0.059			$[Abs\text{- }Ni]_{initial}$	0.15202				Membrane S.A	0.00049			
Pressure (Mpa)	**Samples**	**Abs HA**	**Abs_{avg} HA**	**Stir-cell HA**	**Reject coefficient HA**	**Abs Ni**	**Abs_{avg} Ni**	**Stir-cell Ni**	**Reject coefficient Ni**	**Flask**	**Flask + Sample**	**Sample (L)**	**Time (hr)**	**Jv (LMH)**	**Jv_{avg} (LMH)**
0.02	1									17.3383	21.7428	0.00440	0.1	89.7277	85.7308
	2	0.038	0.038	0.059	0.356	0.137	0.137	0.148	0.070	17.3127	21.6212	0.00431	0.1	87.7720	
	3									17.5831	21.4950	0.00391	0.1	79.6926	
	4	0.059				0.143									
0.04	1	0.046								17.2731	25.5296	0.00826	0.1	168.2000	162.2202
	2	0.048	0.047	0.058	0.183	0.152	0.152	0.154	0.012	17.2929	25.2484	0.00796	0.1	162.0681	
	3	0.047								18.4892	26.1661	0.00768	0.1	156.3925	
	4	0.056				0.156									
0.06	1	0.050								17.4294	32.0436	0.01461	0.1	297.7180	270.9223
	2	0.048	0.048	0.059	0.180	0.155	0.155	0.154	0.000	17.1529	30.0757	0.01292	0.1	263.2611	
	3	0.046								17.3208	29.6804	0.01236	0.1	251.7877	
	4	0.058				0.156									
0.1	1	0.049								17.1772	34.9558	0.01778	0.1	362.1827	349.1820
	2	0.049	0.048	0.060	0.194	0.154	0.154	0.153	0.000	17.2587	34.2231	0.01696	0.1	345.5959	
	3	0.047								17.5226	34.2009	0.01668	0.1	339.7675	
	4	0.061				0.155									
Solution in bottle connected to stir cell		0.059				0.152									
Original solution															

Table 38: CRC 100 kD, n=3, 2 mg/L HA + 1 mg/L Ni, pH = 7, 50 mM KCl (second trial)

		$[Abs- HA]_{initial}$	0.0575			$[Abs- Ni]_{initial}$	0.074				Membrane S.A	0.00049			
Pressure (Mpa)	**Samples**	**Abs HA**	**Abs_{avg} HA**	**Stir-cell HA**	**Reject coefficient HA**	**Abs Ni**	**Abs_{avg} Ni**	**Stir-cell Ni**	**Reject coefficient Ni**	**Flask**	**Flask + Sample**	**Sample (L)**	**Time (hr)**	**Jv (LMH)**	**Jv_{avg} (LMH)**
0.02	1	0.037	0.037	0.065	0.429	0.074	0.074	0.075	0.014	17.6674	22.1073	0.00444	0.1	90.4489	85.6928
	2									17.4506	21.6382	0.00419	0.1	85.3091	
	3									17.2033	21.1951	0.00399	0.1	81.3203	
	4	0.072				0.076									
0.04	1	0.044	0.044	0.059	0.251	0.073	0.073	0.074	0.011	17.8317	25.2807	0.00745	0.1	151.7498	158.7373
	2									17.3494	25.3399	0.00799	0.1	162.7811	
	3									18.3304	26.2669	0.00794	0.1	161.6811	
	4	0.060				0.074									
0.06	1	0.045	0.045	0.059	0.234	0.074	0.074	0.074	0.004	17.3691	29.6390	0.01227	0.1	249.9604	241.3156
	2	0.045								17.4818	28.9030	0.01142	0.1	232.6708	
	3														
	4	0.060				0.075									
0.1	1	0.046	0.047	0.058	0.195	0.074	0.074	0.074	0.004	17.5526	35.3054	0.01775	0.1	361.6571	355.5223
	2	0.047								17.5529	31.8450	0.01429	0.1	349.3875	
	3														
	4	0.058				0.074									
Solution in bottle connected to stir cell		0.061				0.074									
Original solution		0.054													

Table 39: CRC 100 kD, n=3, 2 mg/L HA + 1 mg/L Ni, pH = 7, 50 mM KCl

100kD n=9 CRC, 2mg/L HA + 1mg/L Ni, pH=7, 50 mM KCl															
		$[Abs- HA]_{initial}$	0.091			$[Abs- Ni]_{initial}$	0.08373				Membrane S.A	0.00049			
Pressure (Mpa)	**Samples**	**Abs HA**	**Abs_{avg} HA**	**Stir-cell HA**	**Reject coefficient HA**	**Abs Ni**	**Abs_{avg} Ni**	**Stir-cell Ni**	**Reject coefficient Ni**	**Flask**	**Flask + Sample**	**Sample (L)**	**Time (hr)**	**Jv (LMH)**	**Jv_{avg} (LMH)**
0.02	1	0.047	0.047	0.087	0.4598	0.0833	0.0833	0.08435	0.0124	17.6667	22.2951	0.00463	0.1	94.2890	91.8491
	2									17.1244	21.4874	0.00436	0.1	88.8823	
	3									17.2397	21.7742	0.00453	0.1	92.3761	
	4	0.083				0.08497									
0.04	1	0.051	0.051333333	0.082	0.3701	0.08234	0.08234	0.08341	0.0128	17.7443	26.5303	0.00879	0.1	178.9869	176.3507
	2	0.051								17.1768	25.6560	0.00848	0.1	172.7368	
	3	0.052								17.4505	26.9530	0.00950	0.109	177.3283	
	4	0.072				0.08309									
0.06	1	0.052	0.050666667	0.077	0.3420	0.08343	0.08343	0.083925	0.0059	17.8488	30.6363	0.01279	0.1	260.5048	254.4435
	2	0.05								17.8412	30.2925	0.01245	0.1	253.6558	
	3	0.05								17.8915	30.1226	0.01223	0.1	249.1699	
	4	0.063				0.08412									
0.1	1	0.053	0.053	0.0785	0.3248	0.08394	0.08394	0.084305	0.0043	17.4816	36.2579	0.01878	0.1	382.5076	371.8063
	2	0.054								16.9445	34.9749	0.01803	0.1	367.3123	
	3	0.052								17.2199	35.1662	0.01795	0.1	365.5990	
	4	0.066				0.08488									
Solution in bottle connected to stir cell		0.091				0.08373									
Original solution															

Membrane fouling

Table 40: Membrane fouling of CRC 30kD, unmodified, 8mg/L HA + 1mg/L Ni, pH=7

CRC 30kD n=0, 8mg/L HA + 1 mg/L Ni													
t (min)	Samples	Flask	Flask + Sample	Sample weight	Abs HA	Abs HA Stir cell	HA rejection	Abs Ni	Abs Ni Stir cell	Ni rejection	Sample (L)	Time (min)	Jv/Jv_0
	0	17.595	24.005	6.410	0.038	0.262	0.855	0.032	0.073	0.560	0.006	5	1.0000
15	1	17.634	35.587	17.952	0.040	0.433	0.908	0.037	0.098	0.619	0.018	15	0.9336
30	2	17.789	35.546	17.757	0.041	0.601	0.932	0.040	0.121	0.668	0.018	15	0.9234
45	4	17.844	35.406	17.562	0.041	0.767	0.947	0.042	0.141	0.700	0.018	15	0.9133
60	5	17.408	34.944	17.536	0.041	0.933	0.956	0.037	0.166	0.775	0.018	15	0.9119
75	6	17.417	34.819	17.402	0.046	1.093	0.958	0.037	0.191	0.804	0.017	15	0.9049
90	3	17.598	35.006	17.408	0.048	1.250	0.962	0.037	0.216	0.828	0.017	15	0.9052
105	7	17.674	35.028	17.354	0.049	1.406	0.965	0.038	0.240	0.840	0.017	15	0.9024
120	8	17.368	34.683	17.315	0.050	1.561	0.968	0.039	0.263	0.853	0.017	15	0.9004
135	9	17.317	34.601	17.284	0.050	1.715	0.971	0.042	0.283	0.850	0.017	15	0.8988
150	10	17.345	34.623	17.278	0.050	1.869	0.973	0.044	0.301	0.855	0.017	15	0.8985
165	11	18.496	35.638	17.142	0.050	2.022	0.975	0.045	0.318	0.860	0.017	15	0.8914
180	12	18.330	35.375	17.045	0.055	2.169	0.975	0.045	0.335	0.867	0.017	15	0.8864
195	13	17.230	34.231	17.001	0.057	2.314	0.975	0.043	0.353	0.878	0.017	15	0.8841
210	14	17.779	34.708	16.929	0.053	2.462	0.978	0.045	0.369	0.877	0.017	15	0.8803
225	15	18.103	35.046	16.943	0.054	2.609	0.979	0.046	0.385	0.881	0.017	15	0.8810
240	16	17.255	34.031	16.776	0.055	2.754	0.980	0.047	0.400	0.883	0.017	15	0.8724
Original solution					0.2			0.06133					

Table 41: Membrane fouling of CRC 30kD, n=3, 8mg/L HA + 1mg/L Ni, pH=7

CRC 30kD n=3, 8mg/L HA + 1 mg/L Ni													
t (min)	Samples	Flask	Flask + Sample	Sample weight	Abs HA	Abs HA Stir cell	HA rejection	Abs Ni	Abs Ni Stir cell	Ni rejection	Sample (L)	Time (min)	Jv/Jv_0
	0	18.1471	23.2622	5.1151	0.017	0.26485	0.93581	0.00352	0.08399	0.95809	0.00512	5	1.0000
15	1	17.8375	33.0825	15.2450	0.018	0.43636	0.95875	0.00523	0.13842	0.96222	0.01525	15	0.9935
30	2	17.5467	32.7246	15.1779	0.024	0.60169	0.96011	0.01801	0.18106	0.90053	0.01518	15	0.9891
45	3	17.7810	32.7691	14.9881	0.031	0.75870	0.95914	0.02109	0.22043	0.90432	0.01499	15	0.9767
60	4	17.6001	32.4012	14.8011	0.034	0.91112	0.96268	0.02515	0.25572	0.90165	0.01480	15	0.9645
75	5	17.3908	31.9904	14.5996	0.036	1.05972	0.96603	0.03004	0.28628	0.89507	0.01460	15	0.9514
90	6	17.8756	32.2942	14.4186	0.038	1.20477	0.96846	0.03169	0.31505	0.89941	0.01442	15	0.9396
105	7	17.8698	32.2123	14.3425	0.039	1.34819	0.97107	0.03503	0.34082	0.89722	0.01434	15	0.9347
120	8	17.5109	31.6273	14.1164	0.040	1.48852	0.97313	0.03902	0.36282	0.89245	0.01412	15	0.9199
135	9	17.6505	31.6213	13.9708	0.041	1.62656	0.97479	0.04232	0.38186	0.88917	0.01397	15	0.9104
150	10	18.1106	31.9939	13.8833	0.041	1.76374	0.97675	0.04236	0.40074	0.89430	0.01388	15	0.9047
165	11	17.2626	31.1248	13.8622	0.042	1.89989	0.97789	0.04331	0.41881	0.89659	0.01386	15	0.9034
180	12	17.4688	31.3392	13.8704	0.042	2.03612	0.97937	0.04374	0.43654	0.89980	0.01387	15	0.9039
195	13	17.7971	31.6659	13.8688	0.041	2.17315	0.98113	0.04404	0.45401	0.90300	0.01387	15	0.9038
210	14	17.1273	30.9907	13.8634	0.046	2.30601	0.98005	0.04417	0.47138	0.90630	0.01386	15	0.9034
225	15	17.3240	31.1037	13.7797	0.048	2.43642	0.98030	0.04338	0.48928	0.91134	0.01378	15	0.8980
240	16	17.6805	31.3847	13.7042	0.049	2.56531	0.98090	0.04440	0.50626	0.91230	0.01370	15	0.8931
Original solution					0.207			0.06521					

Extra data

Table 42: CRC 30 kD, unmodified, 2 mg/L HA + 0.5 mg/L Ni, pH = 7

30kD n=0 CRC, 2mg/L HA + 0.5mg/L Ni, pH=7, no ionic strength															
		$[Abs\text{- }HA]_{initial}$	0.058			$[Abs\text{- }Ni]_{initial}$	0.02932				Membrane S.A	0.00049			
Pressure (Mpa)	**Samples**	**Abs HA**	**Abs_{avg} HA**	**Stir-cell HA**	**Reject coefficient HA**	**Abs Ni**	**Abs_{avg} Ni**	**Stir-cell Ni**	**Reject coefficient Ni**	**Flask**	**Flask + Sample**	**Sample (L)**	**Time (hr)**	**Jv (LMH)**	**Jv_{avg} (LMH)**
0.02	1	0.017	0.017	0.089	0.808	0.018	0.018	0.039	0.532	13.7851	16.7412	0.00296	0.1	60.2212	57.9599
	2									13.8907	16.5692	0.00268	0.1	54.5660	
	3									17.3384	20.2391	0.00290	0.1	59.0926	
	4	0.110				0.038									
0.04	1	0.011	0.013	0.094	0.865	0.028	0.028	0.036	0.240	17.3044	23.0987	0.00579	0.1	118.0405	114.3702
	2	0.011								17.5768	23.1569	0.00558	0.1	113.6769	
	3	0.016								17.3737	22.8417	0.00547	0.1	111.3932	
	4	0.130				0.043									
0.06	1	0.015	0.018	0.093	0.802	0.029	0.029	0.038	0.215	13.5957	21.7754	0.00818	0.1	166.6355	166.2070
	2	0.018								14.0374	22.2164	0.00818	0.1	166.6212	
	3	0.022								17.9235	26.0408	0.00812	0.1	165.3643	
	4	0.118				0.040									
0.1	1	0.023	0.024	0.079	0.690	0.036	0.036	0.033	0.000	17.2338	31.0221	0.01379	0.1	280.8929	272.6227
	2	0.027								18.3355	31.7229	0.01339	0.1	272.7259	
	3	0.023								17.4949	30.4662	0.01297	0.1	264.2492	
	4	0.099				0.038									
Solution in bottle connected to stir cell		0.058				0.029									
Original solution															

Table 43: CRC 30 kD, n=3, 2 mg/L HA + 0.5 mg/L Ni, pH = 7

30kD n=3 CRC, 2mg/L HA + 0.5mg/L Ni, pH=7, no ionic strength															
		$[Abs\text{- }HA]_{initial}$	0.058			$[Abs\text{- }Ni]_{initial}$	0.02997				Membrane S.A	0.00049			
Pressure (Mpa)	**Samples**	**Abs HA**	**Abs_{avg} HA**	**Stir-cell HA**	**Reject coefficient HA**	**Abs Ni**	**Abs_{avg} Ni**	**Stir-cell Ni**	**Reject coefficient Ni**	**Flask**	**Flask + Sample**	**Sample (L)**	**Time (hr)**	**Jv (LMH)**	**Jv_{avg} (LMH)**
0.02	1	0.012	0.012	0.0745	0.8389	0.0124	0.0124	0.031565	0.6072	17.1448	19.2993	0.00215	0.1	43.8911	42.6641
	2									17.1718	19.2790	0.00211	0.1	42.9275	
	3									17.9691	19.9902	0.00202	0.1	41.1735	
	4	0.091				0.03316									
0.04	1	0.016	0.0160	0.088	0.8171	0.01408	0.01408	0.03366	0.5817	17.2679	21.4550	0.00419	0.1	85.2989	82.8373
	2									17.4216	21.3720	0.00395	0.1	80.4769	
	3									17.1508	21.2121	0.00406	0.1	82.7361	
	4	0.117				0.03735									
0.06	1	0.01	0.013333333	0.086	0.8441	0.00779	0.00779	0.03611	0.7843	17.7158	23.8524	0.00614	0.1	125.0138	124.4026
	2	0.015								17.6373	23.7841	0.00615	0.1	125.2216	
	3	0.015								17.6340	23.6704	0.00604	0.1	122.9725	
	4	0.113				0.04225									
0.1	1	0.013	0.017333333	0.0945	0.8166	0.00236	0.00236	0.01854	0.8727	17.2801	27.1959	0.00992	0.1	202.0030	199.3330
	2	0.013								17.4620	27.1593	0.00970	0.1	197.5518	
	3	0.026								17.5442	27.2853	0.00974	0.1	198.4441	
	4	0.131				0.00711									
Solution in bottle connected to stir cell		0.058				0.02997									
Original solution															

Table 44: CRC 30 kD, n=9, 2 mg/L HA + 0.5 mg/L Ni, pH = 7

30kD n=9 CRC, 2mg/L HA + 0.5mg/L Ni, pH=7, no ionic strength

Pressure (Mpa)	Samples	Abs HA	Abs_{avg} HA	Stir-cell HA	Reject coefficient HA	Abs Ni	Abs_{avg} Ni	Stir-cell Ni	Reject coefficient Ni	Flask	Flask + Sample	Sample (L)	Time (hr)	Jv (LMH)	Jv_{avg} (LMH)
		$[Abs- HA]_{initial}$	0.067			$[Abs- Ni]_{initial}$	0.03458				Membrane S.A	0.00049			
0.02	1	0.024	0.024	0.089	0.7303	0.00836	0.00836	0.029955	0.7209	13.9577	16.6710	0.00271	0.1	55.2749	55.0759
	2									13.7867	16.4486	0.00266	0.1	54.2278	
	3									18.2145	20.9499	0.00274	0.1	55.7251	
	4	0.111				0.02533									
0.04	1	0.019	0.0240	0.088	0.7257	0.00595	0.00595	0.029705	0.7997	17.6932	23.4450	0.00575	0.1	117.1747	112.3581
	2	0.027								17.7685	23.2429	0.00547	0.1	111.5236	
	3	0.026								17.6999	23.0198	0.00532	0.1	108.3761	
	4	0.108				0.02483									
0.06	1	0.023	0.027666667	0.085	0.6745	0.00826	0.00826	0.036775	0.7754	17.8465	26.2444	0.00840	0.1	171.0806	164.5107
	2	0.029								16.9432	24.9456	0.00800	0.1	163.0236	
	3	0.031								17.4839	25.3098	0.00783	0.1	159.4279	
	4	0.103				0.03897									
0.1	1	0.034	0.032333333	0.0845	0.6174	0.01117	0.01117	0.039175	0.7149	17.5026	30.3749	0.01287	0.1	262.2323	260.0118
	2	0.031								18.2472	30.3099	0.01206	0.1	245.7393	
	3	0.032								17.4927	30.8476	0.01335	0.1	272.0638	
	4	0.102				0.04377									
Solution in bottle connected to stir cell		0.067				0.03458									
Original solution															

Table 45: CRC 30 kD, unmodified, 2 mg/L HA + 2 mg/L Ni, pH = 7

30kD n=0 CRC, 2mg/L HA + 2mg/L Ni, pH=7, no ionic strength

Pressure (Mpa)	Samples	Abs HA	Abs_{avg} HA	Stir-cell HA	Reject coefficient HA	Abs Ni	Abs_{avg} Ni	Stir-cell Ni	Reject coefficient Ni	Flask	Flask + Sample	Sample (L)	Time (hr)	Jv (LMH)	Jv_{avg} (LMH)
		$[Abs- HA]_{initial}$	0.074			$[Abs- Ni]_{initial}$	0.11398				Membrane S.A	0.00049			
0.02	1	0.009	0.009	0.080	0.8868	0.10215	0.10215	0.124575	0.1800	17.7560	20.3563	0.00260	0.1	52.9729	52.8398
	2									17.6385	20.1825	0.00254	0.1	51.8259	
	3									17.5500	20.1870	0.00264	0.1	53.7205	
	4	0.085				0.13517									
0.04	1	0.014	0.0140	0.085	0.8343	0.10121	0.10121	0.126935	0.2027	17.4339	23.0467	0.00561	0.1	114.3430	109.7892
	2									17.2791	22.6150	0.00534	0.1	108.7021	
	3									17.2746	22.4937	0.00522	0.1	106.3226	
	4	0.095				0.13989									
0.06	1	0.019	0.017666667	0.089	0.8015	0.10684	0.10684	0.128955	0.1715	18.0420	26.0208	0.00798	0.1	162.5428	160.0044
	2	0.018								17.3385	25.1791	0.00784	0.1	159.7274	
	3	0.016								17.2632	25.0064	0.00774	0.1	157.7432	
	4	0.104				0.14393									
0.1	1	0.022	0.027	0.1065	0.7465	0.11369	0.11369	0.12417	0.0844	17.3441	30.1633	0.01282	0.1	261.1506	272.6653
	2	0.028								17.8730	30.3506	0.01248	0.1	254.1916	
	3	0.031								17.2087	23.3989	0.00619	0.0	302.6537	
	4	0.139				0.13436									
Solution in bottle connected to stir cell		0.096				0.11398									
Original solution		0.052													

Table 46: CRC 30 kD, n=3, 2 mg/L HA + 2 mg/L Ni, pH = 7

30kD n=3 CRC, 2mg/L HA + 2mg/L Ni, pH=7, no ionic strength															
		$[Abs\text{-}HA]_{initial}$	0.0555			$[Abs\text{-}Ni]_{initial}$	0.12767				Membrane S.A	0.00049			
Pressure (Mpa)	Samples	Abs HA	Abs_{avg} HA	Stir-cell HA	Reject coefficient HA	Abs Ni	Abs_{avg} Ni	Stir-cell Ni	Reject coefficient Ni	Flask	Flask + Sample	Sample (L)	Time (hr)	Jv (LMH)	Jv_{avg} (LMH)
0.02	1	0.006	0.006	0.071	0.9152	0.0056	0.0056	0.12767	0.9561	18.0477	20.0908	0.00204	0.1	41.6217	41.0037
	2									18.2417	20.2375	0.00200	0.1	40.6581	
	3									17.5966	19.5960	0.00200	0.1	40.7314	
	4	0.086				0.08091									
0.04	1	0.011	0.0110	0.073	0.8498	0.05512	0.05512	0.14313	0.6149	18.5325	22.9518	0.00442	0.1	90.0292	87.9425
	2									17.4183	21.7364	0.00432	0.1	87.9676	
	3									17.4383	21.6515	0.00421	0.1	85.8306	
	4	0.091				0.15859									
0.06	1	0.012	0.0125	0.074	0.8305	0.0739	0.0739	0.146865	0.4968	17.6323	24.1695	0.00654	0.1	133.1747	130.5132
	2	0.013								17.4180	23.6939	0.00628	0.1	127.8516	
	3														
	4	0.092				0.16606									
0.1	1	0.016	0.017333333	0.07675	0.7742	0.09273	0.09273	0.14985	0.3812	17.6970	28.6055	0.01091	0.1	222.2261	214.3809
	2	0.016								17.5336	27.9977	0.01046	0.1	213.1729	
	3	0.02								17.1431	27.3407	0.01020	0.1	207.7438	
	4	0.1				0.17203									
Solution in bottle connected to stir cell		0.059				0.12767									
Original solution		0.052													

Table 47: CRC 30 kD, n=9, 2 mg/L HA + 2 mg/L Ni, pH = 7

30kD n=9 CRC, 2mg/L HA + 2mg/L Ni, pH=7, no ionic strength															
		$[Abs\text{-}HA]_{initial}$	0.0535			$[Abs\text{-}Ni]_{initial}$	0.12861				Membrane S.A	0.00049			
Pressure (Mpa)	Samples	Abs HA	Abs_{avg} HA	Stir-cell HA	Reject coefficient HA	Abs Ni	Abs_{avg} Ni	Stir-cell Ni	Reject coefficient Ni	Flask	Flask + Sample	Sample (L)	Time (hr)	Jv (LMH)	Jv_{avg} (LMH)
0.02	1	0.009	0.009	0.069	0.8691	0.00918	0.00918	0.108805	0.9156	17.4719	19.9341	0.00246	0.1	50.1595	49.3066
	2									17.4082	19.8240	0.00242	0.1	49.2143	
	3									17.6792	20.0622	0.00238	0.1	48.5461	
	4	0.084				0.089									
0.04	1	0.017	0.0197	0.080	0.7534	0.0479	0.0479	0.14721	0.6746	17.1757	22.5947	0.00542	0.1	110.3950	110.1064
	2	0.02								17.5733	22.8901	0.00532	0.1	108.3130	
	3	0.022								17.8540	23.3327	0.00548	0.1	111.6112	
	4	0.106				0.16581									
0.06	1	0.026	0.024333333	0.066	0.6327	0.05542	0.05542	0.141935	0.6095	17.4787	25.6476	0.00817	0.1	166.4155	159.0680
	2	0.025								17.3089	25.1147	0.00781	0.1	159.0185	
	3	0.022								17.6680	25.1180	0.00745	0.1	151.7702	
	4	0.079				0.15526									
0.1	1	0.03	0.030333333	0.07275	0.5830	0.06799	0.06799	0.144665	0.5300	17.4177	31.9975	0.01458	0.1	297.0172	281.0681
	2	0.03								17.4577	31.0800	0.01362	0.1	277.5112	
	3	0.031								18.0613	31.2499	0.01319	0.1	268.6760	
	4	0.092				0.16072									
Solution in bottle connected to stir cell		0.055				0.12861									
Original solution		0.052													

Standard line of Ni concentration- absorbance

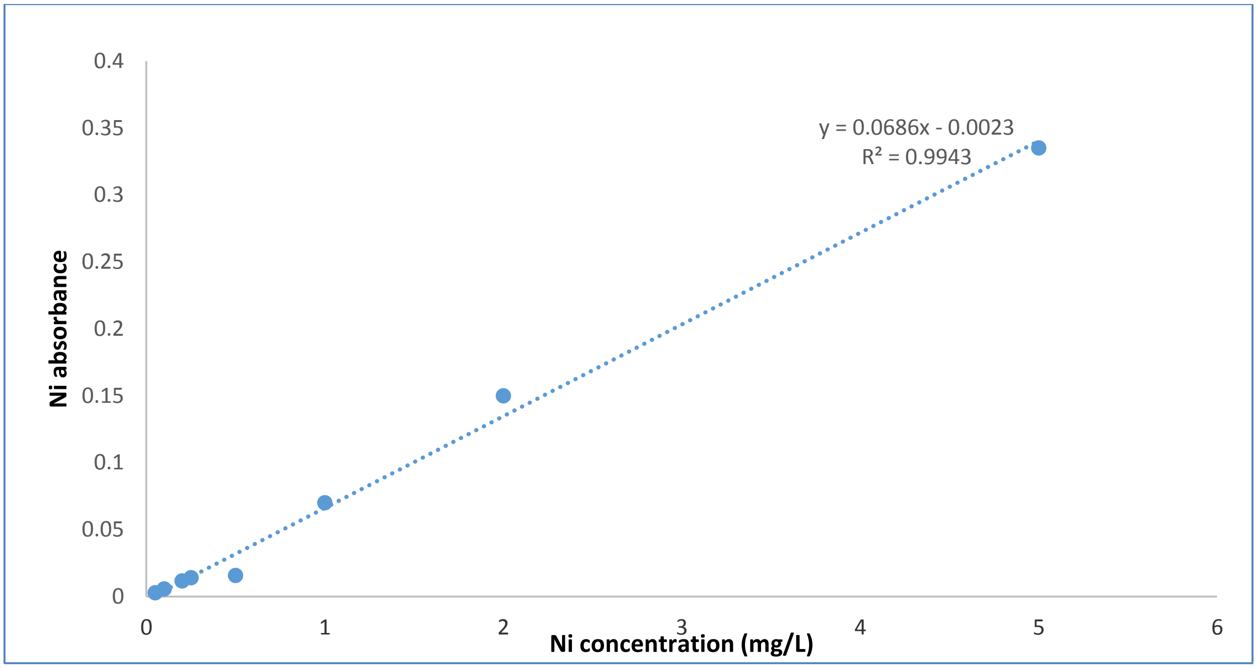

Figure 30: Ni absorbance versus Ni concentration

Table 48: Ni absorbance versus Ni concentration

Conc Ni	Abs Ni
0.05	0.0028
0.1	0.00581
0.2	0.01179
0.25	0.01408
0.5	0.01572
1	0.07
2	0.14988
5	0.33526

Lp data

Table 49: CRC 100 kD, unmodified, pure water

P (MPa)	P (kPa)	f (g)	f + s (g)	t (s)	$d_{membrane}$ (mm)	SA membrane (m^2)	Solution volume (L)	J_v (LMH)
0.0176	17600	17.8481	18.6733	61	25	0.000490874	0.0008252	99.21149
0.0463	46300	18.6733	20.8035	60	25	0.000490874	0.0021302	260.3765
0.0632	63200	20.7937	23.6261	61	25	0.000490874	0.0028324	340.5315
0.0901	90100	23.6261	27.3807	60	25	0.000490874	0.0037546	458.9285

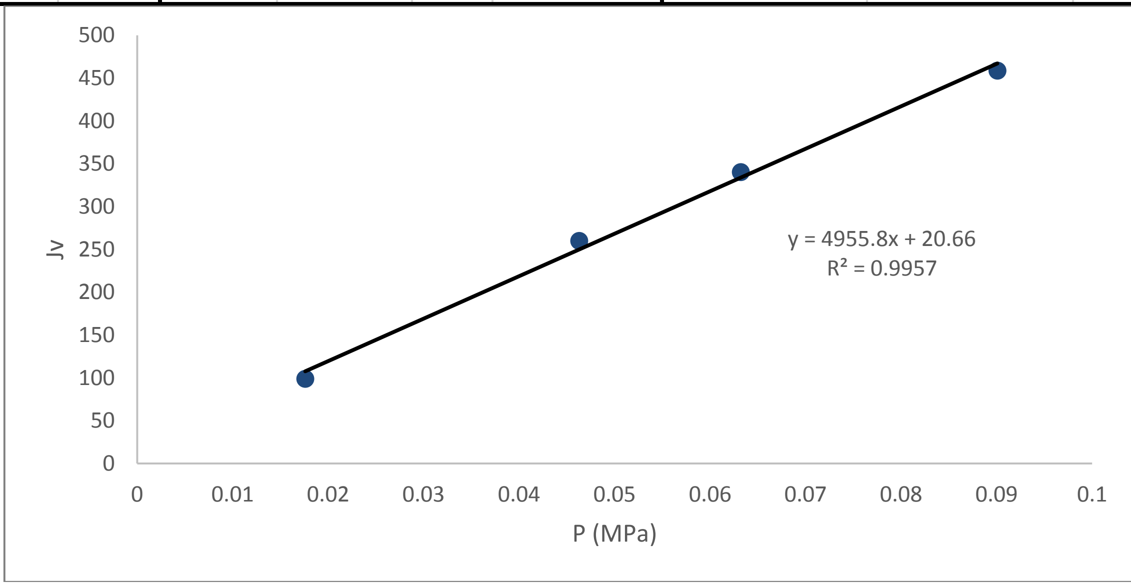

Figure 31: Lp of CRC 100 kD, unmodified, pure water

Table 50: CRC 100 kD, n=3, pure water

$P_{initial}$ (Mpa)	P_{final} (Mpa)	P (MPa)	P (kPa)	f (g)	f + s (g)	t (s)	$d_{membrane}$ (mm)	SA membrane (m^2)	Solution volume (L)	J_v (LMH)
0.012	0.011	0.012	12000	17.4974	17.8195	60	25	0.000490874	0.0003221	39.3706
0.0425	0.0421	0.042	42000	17.8195	19.0708	60	25	0.000490874	0.0012513	152.9476
0.063	0.061	0.062	62000	19.0708	20.9139	60	25	0.000490874	0.0018431	225.2839
0.0831	0.081	0.082	82000	20.9139	23.2335	60	25	0.000490874	0.0023196	283.527

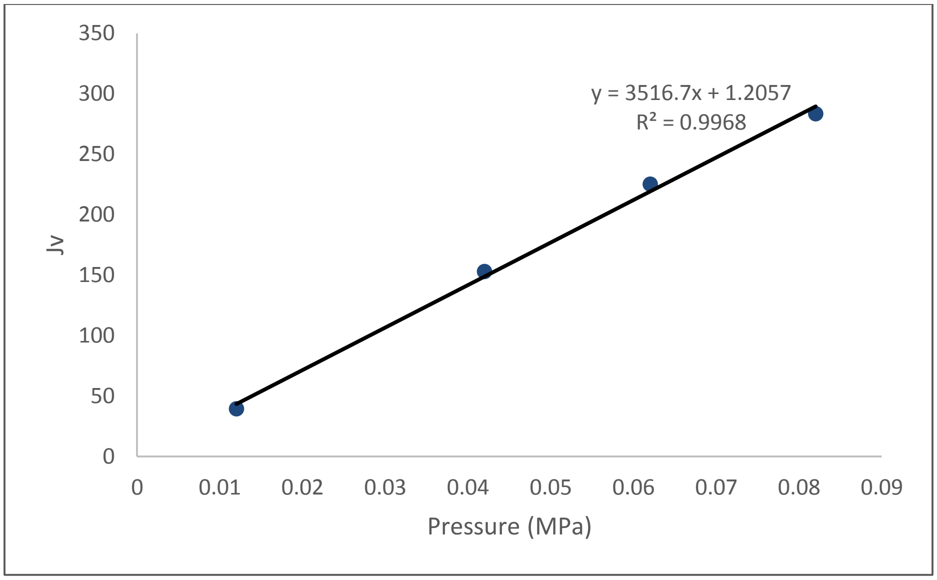

Figure 32: Lp of CRC 100 kD, n=3, pure water

Table 51: CRC 100 kD, n=9, pure water

$P_{initial}$ (Mpa)	P_{final} (Mpa)	P (MPa)	P (kPa)	f (g)	f + s (g)	t (s)	$d_{membrane}$ (mm)	SA membrane (m^2)	Solution volume (L)	J_v (LMH)
0.02	0.0218	0.021	21000	13.3273	14.1533	60	25	0.000490874	0.000826	100.9628
0.0398	0.0389	0.039	39000	14.1533	15.6672	60	25	0.000490874	0.0015139	185.0455
0.0607	0.0611	0.061	61000	15.6672	17.9467	60	25	0.000490874	0.0022795	278.6256
0.0803	0.0789	0.08	80000	17.9467	20.8251	60	25	0.000490874	0.0028784	351.8297

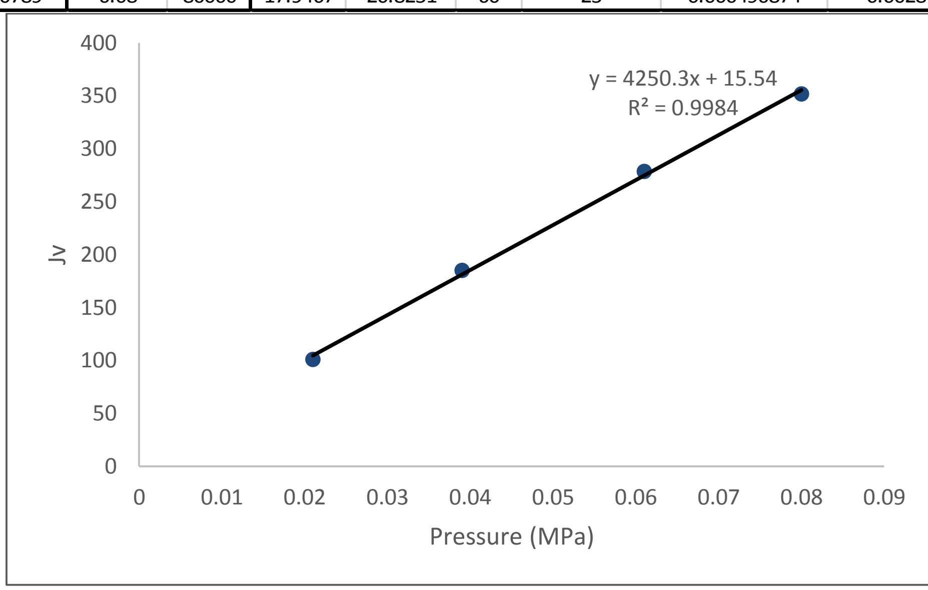

Figure 33: Lp of CRC 100 kD, n=9, pure water

Table 52: CRC 30 kD, unmodified, pure water

$P_{initial}$ (Mpa)	P_{final} (Mpa)	P (MPa)	P (kPa)	f (g)	f + s (g)	t (s)	$d_{membrane}$ (mm)	SA membrane (m^2)	Solution volume (L)	J_v (LMH)
0.02	0.0191	0.02	20000	18.3647	18.7893	60	25	0.000490874	0.0004246	51.89928
0.04	0.0389	0.039	39000	18.7893	19.659	60	25	0.000490874	0.0008697	106.3043
0.0592	0.057	0.058	58000	19.659	20.9291	60	25	0.000490874	0.0012701	155.2456
0.082	0.0819	0.082	82000	20.9291	22.7182	60	25	0.000490874	0.0017891	218.6835

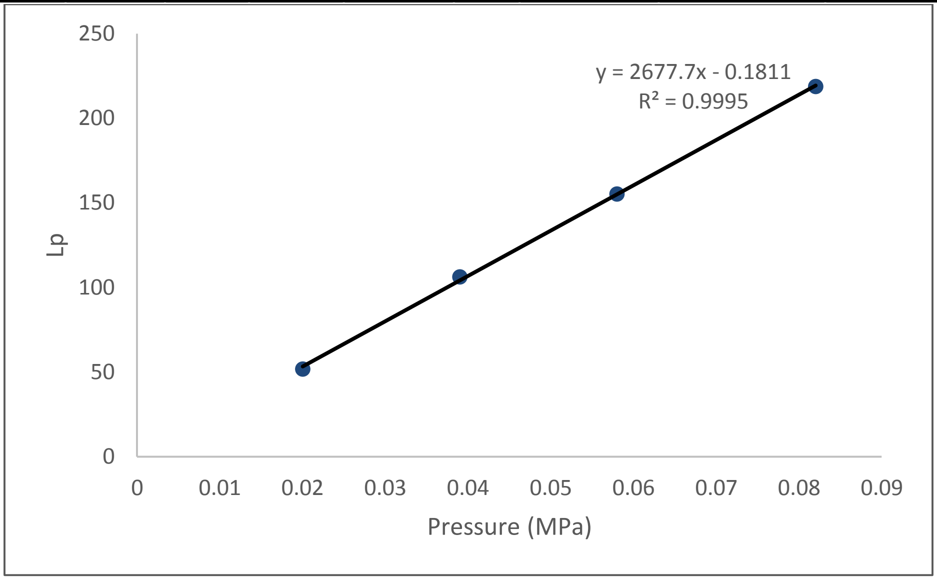

Figure 34: Lp of CRC 30 kD, unmodified, pure water

Table 53: CRC 30 kD, n=3, pure water

$P_{initial}$ (Mpa)	P_{final} (Mpa)	P (MPa)	P (kPa)	f (g)	f + s (g)	t (s)	$d_{membrane}$ (mm)	SA membrane (m^2)	Solution volume (L)	J_v (LMH)
0.0201	0.02	0.02	20000	22.7179	23.1111	60	25	0.000490874	0.0003932	48.06123
0.042	0.043	0.043	43000	23.1111	23.9159	60	25	0.000490874	0.0008048	98.37151
0.0611	0.0605	0.061	61000	23.9159	25.0526	60	25	0.000490874	0.0011367	138.94
0.0802	0.0825	0.081	81000	25.0526	27	60	25	0.000490874	0.0015736	192.3427

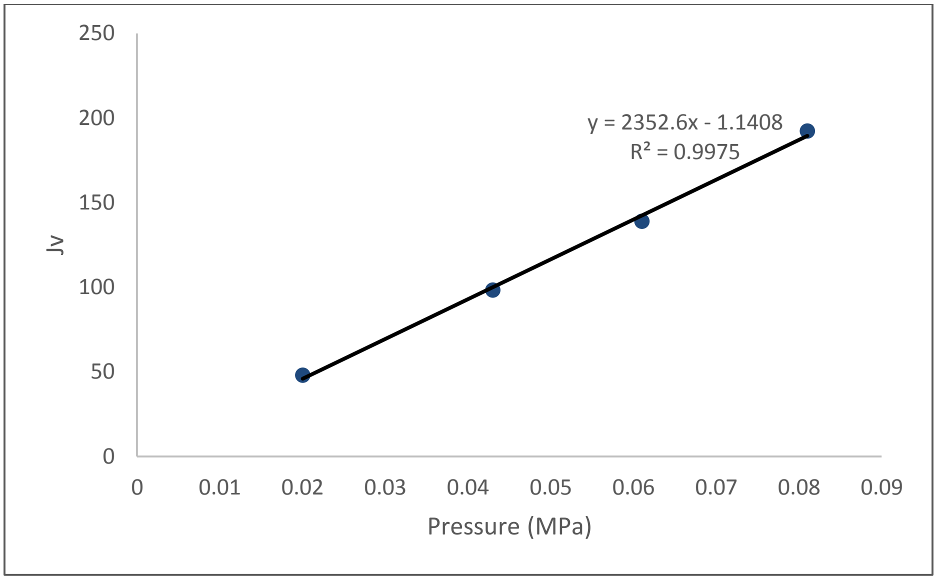

Figure 35: Lp of CRC 30 kD, n=3, pure water

Table 54: CRC 30 kD, n=9, pure water

$P_{initial}$ (Mpa)	P_{final} (Mpa)	P (MPa)	P (kPa)	f (g)	f + s (g)	t (s)	$d_{membrane}$ (mm)	SA membrane (m^2)	Solution volume (L)	J_v (LMH)
0.021	0.021	0.021	21000	17.4428	17.7484	60	25	0.000490874	0.0003056	37.35379
0.0409	0.039	0.04	40000	17.7484	18.4257	60	25	0.000490874	0.0006773	82.78705
0.0631	0.0625	0.063	63000	18.4257	19.5335	60	25	0.000490874	0.0011078	135.4075
0.078	0.078	0.078	78000	19.5335	21	60	25	0.000490874	0.0014041	171.6245

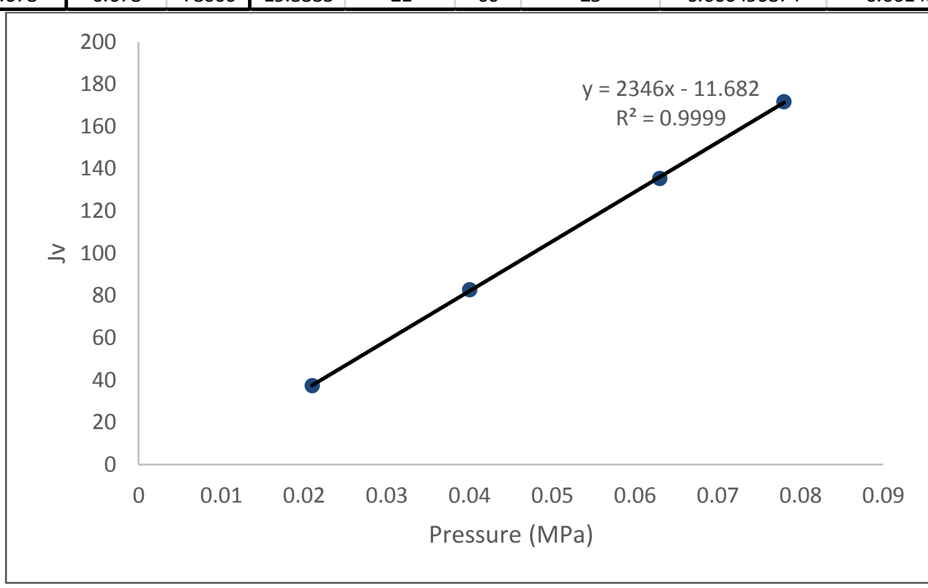

Figure 36: Lp of CRC 30 kD, n=9, pure water