**using permeate suction to reduce concentration polarization in spiral wound nanofiltration module**

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**Abstract:**

Fouling in a nanofitration membrane module is usually a result of concentration polarization. The effect of permeate suction on the slightly negatively charged spiral wound nanofiltration membrane is investigated. According to the film theory, the mass transfer coefficient is inversely proportional to concentration polarization. The effect of permeate suction destabilizes the boundary layer. This will decrease the concentration polarization layer, and consequently will increase mass transfer through the membrane’s surface.

To validate the hypothesis, experiments were carried out on a NF membrane that can be described by the solution-diffusion model. This model has coefficients that can be measured experimentally. Using the membrane wall concentration in this model instead of the bulk feed concentration can help estimating the mass transfer coefficient more appropriately.

Two experimental studies were carried out, one with a standard high pressure pump, and another one with the added effect of suction pressure applied to the permeate

collector tube.

Three different concentrations of binary dilute solutions of *NaCl* , *MgSO*4 , and *MgCl*2 , at three different pressures (low, medium, and high) were tested.

For all tested solutions, permeate suction increased the diffusive Peclet number as a function of the feed

concentration. With the increase of the Peclet number, it was observed that the concentration polarization decreased, and both the product flow and the product quality were improved.

It was concluded that permeate suction reduced concentration polarization, increased product flow rate, and improved product quality. Thus, adding permeate suction has beneficial consequences because it reduces membrane fouling and extends its useful service life.

**INTRODUCTION**

 Membrane fouling and scaling can significantly increase the cost of a membrane system as well as reduce its reliability. Fouling is a term generally used to describe the undesirable formation of deposits on the surface of the membrane. Membrane fouling is a complicated phenomenon because it results from a group of physical, chemical, and biological effects that can lead to an irreversible loss of membrane permeability [1]. Several techniques that have the potential to reduce the concentration polarization to control the fouling have been adopted and proposed.

The rapid growth of the new generations of nanofiltration membrane [2] as an attractive membrane separation process suggests renewed investigations of the current design methods for developing an improved design configuration to reduce membrane fouling. Spiral wound configuration, which is the most dominant module used in the application of pressure driven membrane for drinking water treatment, was rarely investigated by researchers as far as the permeate suction is concerned.

In the laminar flow fluid stream of RO/NF membranes, flow separation happens due to velocity deficit at the boundary layer adjacent to the membrane surface [3].

By applying suction at the end of the permeate collector tube of the membrane module, an increase of pressure along the stream will present. This increase in pressure will destabilize the boundary layer [3]. It is assumed that it will consequently destabilize the concentration polarization layer.

The mass transfer coefficient is the most widely used parameter in the design of pressure-driven membrane separation system such as reverse osmosis and nanofiltration [4].

 The diffusive Peclet number is a measure of how permeate goes through the membrane [5].

If Peclet number is increased due to suction, while the associated concentration polarization is being reduced, then suction will increase membrane production with more favorable conditions to the membrane, as far as inorganic fouling is concerned.

**OBJECTIVE**

 The objective of this research is to investigate the effect of permeate suction on the mass transfer coefficient, concentration polarization layer, and membrane diffusive peclet number for spiral wound NF module. The goal is to increase system permeate flow and quality without subjecting the membrane to an increasing tendency for inorganic precipitation. This will be carried out by comparing the data collected from running two tests on the membrane, once with using the standard high pressure feed pump only, and then running the test after adding the effect of the permeate suction pump to the original setup. Results will be compared between both setups after running the experiments.

**APPROACH**

 For the slightly negatively charged nanofiltration membrane applications, the water flux can be presented by the solution diffusion model [6]. Most of the parameters in this model can be experimentally measured. This is opposite to the charged membrane theoretical models like Donnan equilibrium model [7] that used to describe NF membranes. The later models have parameters difficult to be measured in reality [8]. Furthermore, for dilute solutions, which are the typical solutions fed to NF membrane, the convection term is so small such that it can be neglected [6] to further simply the real model.

 Mass transfer models typically assume that the bulk feed solution concentration is equal to the membrane wall solution concentration, which is not always true. This has to be related to the concentration polarization expressions. Concentration polarization complicates the modeling of membrane systems [7] because it is

very difficult to experimentally determine the solute membrane surface concentration ()

 as shown in Figure (1).

 *Figure 1. Feed side concentration polarization layer*

Membrane surface concentration is necessary to be determined since it and not the bulk feed concentration () should be used for hyperfiltraion (RO and NF) membrane processes.

The permeate suction will be tested, and will be experimentally validated for NF spiral wound TFC module in this research. An experimental setup for the membrane system will be tested with the conventional operating setup in order for it to be compared with the permeate suction setup results.

The research will be conducted for three different dilute strong electrolyte solutions, namely:,, , which are 1-1, 2-1, and 2-2 electrolytes [11], respectively, at three different pressures and three different dilute concentrations. The experiment will be set at a constant temperature of 25 degrees Celsius in order to keep the diffusion coefficient constant for the different dilute solutions.

**THEORY**

 The Reverse Osmosis solution diffusion model assumes that the water transport across the membrane is only by diffusion, and so can be expressed by Fick’s low (6) as:

 = - (1)

where cand Dare the concentration, and the diffusivity coefficient of water in the membrane, respectively.

On a stagnant boundary layer over the channel length, and by integration we can get the following equation:

 = exp (2)

This is the widely applied film theory developed by Brian [8].

 The ratio of the diffusion coefficient for solute transport through solvent to the concentration polarization layer thickness in this film theory model defines a mass transfer coefficient K:

 K **=**  (3)

Using above equations (2) and (3), the concentration polarization layercan be calculated.

For dilute solutions, if pore flow is neglected, the water flux is given by: (6)

 = A (- ) (4)

Where A is the membrane solvent permeability coefficient and it is the property of the membrane; is the operating pressure; is the difference in the osmotic pressure across the membrane.

The termis equal to the difference between the osmotic pressure at the membrane surface minus the permeate osmotic pressure. For dilute solutions the osmotic pressure is independent of the solute species, and is given by Van’t Hoff equation (4):

 = RT (5)

 Where = number of ions formed when the solute dissociates.

And = molar concentration of the solute = / 1000

and = total dissolved solids as mg/l ;

= molecular weight of the dilute solution;

R= gas constant; and T= absolute temperature.

From equations (4) and (5) above, membrane wall concentration C can be calculated.

**EXPERIMENTS**

 The feed water for all the experiments is prepared using de-ionized (DI) water and analytical grade salts. Only simple binary solutions of,, and - which are 1-1, 2-1, and 2-2, respectively, strong electrolyte dilute solutions [11] - are considered in this research. The diffusion coefficients for the binary solutions were calculated using the equations from Cussler [9].

Three experiments were run for the three different concentrations for low, medium, and high values of the applied feed pressures.

**1. Experimental Setup**

 As shown on the schematic flow diagram Figure (2), solutions were pumped from a HDPE feed tank by a booster pump to the high pressure pump through 5 m cartridge filter to protect the pump, and the membrane from any suspended solids that may be available in the solution tank.

At the beginning of the experiments, the pure water permeability coefficient (A) was calculated using equation (4) above.

The membrane permeability coefficient A can be determined from distilled water where in this case is approximately equal to zero.

 The term is the hydraulic pressure difference across the membrane, and is equal to the applied membrane pressure minus the permeate pressure, while is the permeate flux, and is equal to the permeate flow rate divided by the membrane cross flow area.

The NF membrane tested is a standard size commercial 2.5 inch nominal diameter, and 40 inch long spiral wound aromatic polyamide thin-film composite membrane Model NF270- 2540, manufactured by Dow-FilmTec Inc. The effective surface area is 28(2.6) [10].

 *Figure 2. Setup of running the high pressure pump and the permeate suction pump*

**RESULT AND DISSCUSSION**

* **Concentration Polarization Layer Thickness:**

 Figure (3) is plotting the trend in concentration polarization layer thickness against the net operating pressure (-) forsolutions. The solid line is showing the trend with permeate suction, while the dotted line is presenting the trend without permeate suction. For example, at a net operating pressure of 5.45 atm, the average concentration polarization layer thickness without permeate

suction was 7.9 x m. This was reduced to about 6.7 x m with permeate suction, resulting in a reduction of about 15 %. Figure (3) illustrates that the permeate suction de-stabilizes the boundary layer in the laminar flow condition that reduces concentration polarization. For dilute solutions like the feed to NF, the concentration polarization layer thickness increases with the increase of the operating pressure of the feed. Similar results were also observed for and solutions.



*Figure 3. Concentration polarization layer thickness versus net operating pressure -*

**2- Mass Transfer Coefficient:**

 As was mentioned above, the mass transfer coefficient is inversely proportional to the concentration polarization layer thickness. Figure (4) shows that the mass transfer coefficient for all dilute solutions of has increased with permeate suction, if compared with the case of no permeate suction.

Again, it is deduced that the permeate suction de-stabilizes the boundary layer in the laminar flow condition that reduces concentration polarization and enhances the mass transfer coefficient.

Similar results were observed for all and solutions.



*Figure 4. Mass Transfer Coefficient* *versus feed concentration -*

* **Peclet Number:**

 In the case of using the standard high pressure pump only, both the permeate concentration and the concentration polarization layer increase as the Peclet number increases [5]. However Figure (6) shows a very remarkable result. It shows that the diffusive Peclet number for the binary dilute solutions of has increased with the permeate suction at all pressures, although the associated concentration polarization layer thicknesses have decreased as was discussed in item (1) above.

The same results were observed forand solutions.

This is a proof that the permeate suction has destabilized the flow conditions, and has enhanced the mass transfer coefficient due to the reduction in concentration polarization thickness.



*Figure 5. Diffusive Peclet number versus feed concentration –*

**CONCLUSION**

 The technique of using permeate suction is not practically used in the NF or RO membrane industry so far, despite that it has been theoretically investigated at the laboratory scale by a few researchers.

* This research showed that when using binary dilute solutions, the permeate suction reduced the concentration polarization at the feed side of the industry scale NF membrane surface that helped to increase mass transfer coefficient, improve product quality, and increase the product flux without subjecting the membrane to less favorable conditions.
* The applications of NF membrane in the water treatment industry are numerous, and based on the above-mentioned results using the permeate suction can help reduce the concentration polarization layer in NF modules, and increase mass transfer coefficient, that will elongate the useful membrane life and reduce the total water cost.

**THE PROMISE OF THIS RESEARCH**

* The encouraging results of this research makes us believe that extending the application of permeate suction to the higher concentration of brackish water RO modules, or even seawater RO plants can critically be investigated, despite the complexity of predicting the mass transfer model for highly concentrated mixed salt solutions.
* The recent evolution of one American company using Nano technology to double or even triple the flux of the membrane is opening the door to run the RO plants with higher flux when permeate suction is used, that may double the plant capacity without major changes to the current designs.
* An innovated design of a NF plant built recently at Jupiter City Water Treatment Plant at Florida that uses pressure vessels with two concentrate outlets at its center can also enhance the membrane performance, since this idea helps reducing the concentration polarization at the membrane surface.

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