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Water fluxes in Forward Osmosis

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ملخص البحث

أصبحت موارد المياه المتجددة أحد الموضوعات الرئيسية التي تتم دراستها في الوقت الحاضر. واحدة من التقنيات الراسخة في الحصول على المياه العذبة هي استخدام التناضح العكسي . لقد أصبح التناضح العكسي واحد من موارد المياه العذبة الرئيسية في العديد من المناطق وخاصة في بلدان الإجهاد المائي ، وذلك ببساطة لأنه يستخدم أي مصدر من المياه المعطوبة سواء كان من البحر أو البحيرات أو الأنهار لإنتاج مياه الشرب العذبة. في التناضح العكسي ، يجب استخدام الضغط الخارجي الذي يزيد عن الضغط الاسموزي للسائل الذي يتم تنقيته من أجل دفع الماء النقي من خلال غشاء نصف نافذ تاركًا وراءه جميع الملوثات. وبالتالي فإن التحدي الرئيسي مع التناضح العكسي هو الطاقة العالية المطلوبة للتشغيل. مشكلة أخري من مشاكل التناضح العكسي هو تلف الغشاء الفاصل بين المياه المعطوبه و المياه النقية و ذلك نتيجة تراكم الملوثات عليه تحت ضغط عالي وذاك يتطلب تنظيفًا ميكانيكيًا وكيميائيًا لعكس تأثير تراكم الملوثات، مما يفرض تكلفة إضافية على الأداء الكلي. أتت من هنا فكرة استخدام التناضح الأمامي في تنقية المياه والتي تستخدم فرق الضغط الاسموزي الطبيعي بين سائلين للسماح بالتدفق الطبيعي للمياه عبر غشاء نصف نافذ من محلول ذو التركيز المنخفض إلى المحلول ذو التركيز الأعلى. لنكون قادرين على إمكانية تفعيل بعض التطبيقات بإستخدام التناضح الامامي فمن المطلوب تقييم أداء غشاء FO متاح تجاريا. لذلك في هذه الدراسة تم تقييم أداء الغشاء FO المتاح تجارياً باستخدام تجربة بسيطة في المختبر حيث تم حساب تدفقات المياه وتدفقات الملح العكسي لتركيزات مختلفة للملح. تم العثور على ان تدفق المياه وتندفق الأملاح يزيد زيادة لوغاريتمية مع زيادة تركيز الملح.

Abstract

Renewable water resources are becoming one of the major topics being studied nowadays . One of the well-established technologies in obtaining fresh water is using Reverse Osmosis (RO). It has become one of the main fresh water resources in many regions especially in water stressed countries, simply because it utilizes any source of impaired water whether it is from seas, lakes or rivers to produce fresh potable water. In RO an external pressure that is in excess of the osmotic pressure of the liquid being purified must be applied in order to push pure water through a semipermeable membrane leaving behind all foulants. Thus the main challenge with RO is the high energy required for operation. Also RO has a high fouling potential because the foulants are being compressed against the membrane and require mechanical and chemical cleaning in order to reverse the effect of fouling which poses an extra cost on the overall performance. From here came the idea of using forward osmosis in water purification which utilizes the natural osmotic pressure difference between two liquids to allow for the natural flow of water through a semi permeable membrane from the lower concentration solution (feed solution-

FS) to the higher one (draw solution-DS). to be able to evaluate the potentiality of some applications it is required first to evaluate the performance of a commercially available FO membrane. So in this study the performance of a commercially available FO membrane was evaluated using a simple lab scale experiment in which water fluxes and reverse salt fluxes were calculated for different salt concentration. Water flux and RSF were found to increase logarithmically with the increase in salt concentration.

1. Introduction

Renewable water resources are becoming one of the major topics being studied nowadays . One of the well-established technologies in obtaining fresh water is using Reverse Osmosis (RO). It has become one of the main fresh water resources in many regions especially in water stressed countries, simply because it utilizes any source of impaired water whether it is from seas, lakes or rivers to produce fresh potable water. In RO an external pressure that is in excess of the osmotic pressure of the liquid being purified must be applied in order to push pure water through a semipermeable membrane leaving behind all foulants. Thus the main challenge with RO is the high energy required for operation. Also RO has a high fouling potential because the foulants are being compressed against the membrane and require mechanical and chemical cleaning in order to reverse the effect of fouling which poses an extra cost on the overall performance[1]. From here came the idea of using forward osmosis in water purification which utilizes the natural osmotic pressure difference between two liquids to allow for the natural flow of water through a semi permeable membrane from the lower concentration solution (feed solution-FS) to the higher one (draw solution-DS). Full scale FO plants have not yet been widely used except for one in Oman because it was found that the total cost of operating an FO plant which includes the extraction of the draw solutes is more expensive or equal to operating an RO plant making RO plants a more preferable option as it is a well-established technology with all parts available.

2. The osmotic process

2.1. Definition

The concept of osmosis is that when two liquids of different salt concentrations are placed with a selectively permeable membrane in between, two drag forces occur. The first one would be that of water flowing from the lower concentration solution -feed solution (FS) to the higher concentration solution- Draw Solution (DS) trying to reach equilibriun, i.e. a state where both solution would have equal salt concentrations. The rate at which water crosses the membrane is the water flux. The second force would be that of the salt particles, flowing from the DS to the FS aiming to reach equilibrium. The rate at which the salt flows is the reverse salt flux (RSF). Many parameters affect the water flux and the RSF but the two major ones are the salt concentrations of both solutions and the membrane type. A higher salt concentration gradient results in higher fluxes. Many parameters affect the membrane type. A good membrane is one that provides high water permeability and high salt rejection i.e. low RSF, however higher water permeability is usually accompanied with higher salt fluxes and thus new membranes are being developped each day to better meet both criteria.

Water purification using forward osmosis includes the use of a high salinity solution (DS) which would draw clean water from an impaired water source through a semipermeable membrane, leaving behind all foulants, followed be the separation of the draw solution and pure water. Many challenges stand in the way of implementing this technology on a full scale like the very low water fluxes that occur which results in very low recovery rates, extraction of the draw solution can be quite costly making the whole process more expensive than the traditional RO, and an ideal membrane that allows for high water permeability ,high salt rejection and minimizes the internal concentration polarization is still being developed.

2.2 water extraction using forward osmosis

The process of water extraction using FO involves two steps as illustrated in figure (1). The first step is the FO process where water migrates from an impaired water source to the draw solution causing continuous concentration of the feed solution and dilution of the draw solution. The second step involves the extraction of the draw solutes from the diluted draw solution in order to give the permeate water and the concentrated draw solutes which can be recycled into the system once more.

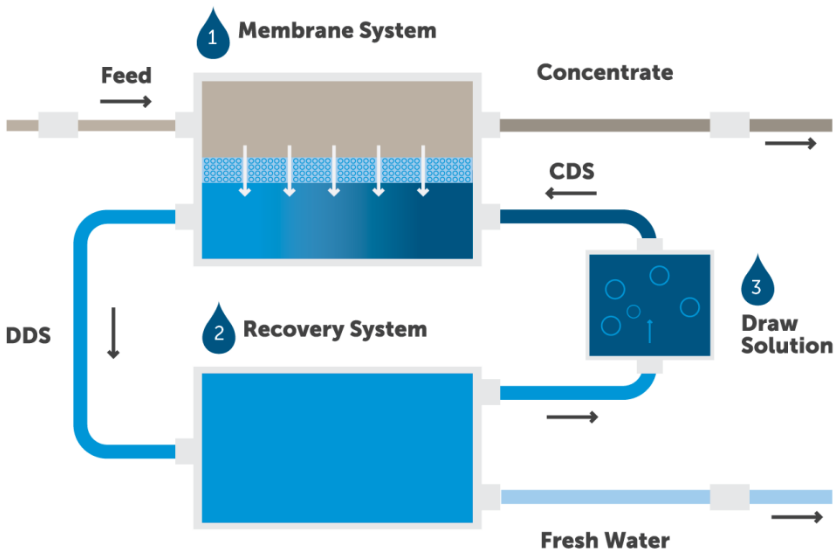

Figure 1:water extraction process

2.3 Membranes

Membranes are usually asymmetric and consist of two layers: a high density active layer which is responsible for the salt rejection and a porous support layer which is to protect the active layer from breaking[3]. A good membrane should be able to reject the feed and draw molecules and provide high water fluxes.

There are two modes of orientation for the membrane. The FO mode where the active layer is facing the feed solution and the PRO mode where the support layer is facing the feed solution. The choice of membrane orientation mainly depends on the application.

New membranes are being developed everyday trying to reach an ideal membrane minimizes internal concentration polarization and minimizes reverse solute flux and has a high resistance to fouling.

2.4 Draw Solution

The draw solution is the source of the driving force in the forward osmosis process. The higher the concentration of the draw solution, the higher the flux is. A good draw solution should be able to generate high osmotic pressure at a low viscosity, should have a molecular size that is small enough to minimize ICP yet large enough to minimize the reverse solute flux[2]. It should be inexpensive, highly soluble and could be extracted using efficient techniques [1]. There are many possible draw solutions available that could be used, but the selection of the draw solution mainly depends on the application. Possible draw solutions include: $CaCl_2$, $KHCO_3$, $MgCl_2$, $MgSO_4$,$NaHCO_3$, $KHCO_3$, $MgSO_4$, NaCl, $NaHCO_3$ and Na_2SO_4.

There are many possible ways for the draw solution extraction which includes: Reverse osmosis (RO), membrane distillation (MD), thermal separation, Nano filtration, and ultra-filtration.

2.5 concentration polarization

This phenomenon and its impact on the net driving osmotic pressure is one of the most significant factors in osmotically driven processes, primarily because of the membrane support layer[4]. There are two types of concentration polarization (CP) according to where they occur, if the CP occurs inside the support layer of the membrane then it is called internal concentration polarization (ICP), but if the CP occurs outside the support layer then it is called external concentration polarization. Figure 3 shows the two membrane orientations that can be used. For the FO mode, the membrane active layer faces the feed solution while in PRO mode the membrane active layer faces the draw solution.

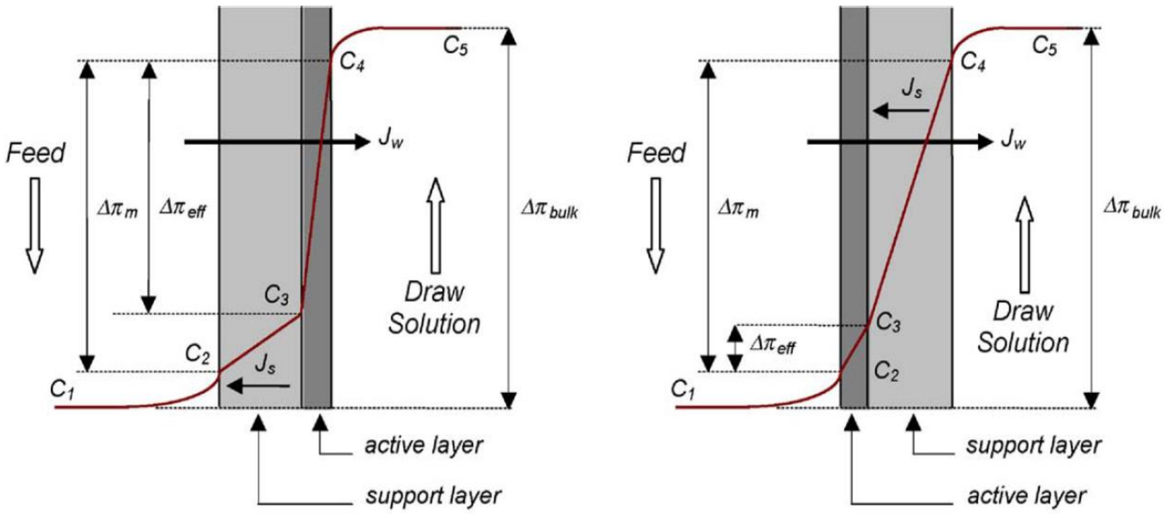

Figure 2: schematic explaining the concentration polarization in the FO mode and PRO mode

2.5.1 Internal concentration polarization (ICP)

In FO mode, as the water permeates from the FS to the draw solution, dilution of the draw solution occurs inside the support layer thus decreasing the effective osmotic pressure across the membrane active layer, this is called dilutive ICP. While in PRO mode the solutes moving due to RSF from the DS to the FS get concentrated in the support layer, increasing the feed concentration thus increasing the effective osmotic pressure of the feed solution. This is called concentrative ICP. Both internal concentration polarization decrease the difference in effective osmotic pressure between the feed and draw solutions and thus decreasing the overall water flux across the membrane. Usually ICP is irreversible and cannot be mitigated by changing the hydraulic parameters of the flowing liquid.

2.5.2 External concentration polarization (ECP)

In FO mode, as the solutes move from the DS to the FS, the concentration of the FS increases and the effective osmotic pressure increases, while in PRO mode, as water permeates from the FS to the DS, dilution of the DS occurs and thus decreasing the effective osmotic pressure on the draw side. Both external concentration polarization decrease the difference in effective osmotic pressure between the feed and draw solutions and thus decreasing the overall water flux across the membrane, but the effect of the ECP is usually less severe than the ICP and can be mitigated by changing the flow hydraulic parameters.

Figure 3 shows the two membrane orientations that can be used. For the FO membrane orientation.

2.6 Governing equations

The general equation describing water transport in FO is

$$J_w = A\left[\pi_{D,b}\exp(-J_w K) - \pi_{F,b}\exp\left(\frac{J_w}{k}\right)\right]$$

where J_w is the water flux, A the water permeability constant of the membrane, $\pi_{D,b}$ and $\pi_{F,b}$ are the bulk osmotic pressure of the draw and feed solutions respectively. k is the mass transfer coefficient and given by:

$$k = \frac{ShD}{d_h}$$

Where Sh is sherwood number, D is the bulk diffusion coefficient for the draw solution and D_h is the membrane channel hydraulic diameter. K is the Solute resistance to diffusion and given by:

$$K = \frac{t\tau}{\varepsilon D} = \frac{S}{D}$$

Where t is the thickness of the support layer, τ is the tortuosity of the support layer and e is the porosity of the support layer

3. Potential applications

Many possible applications are being considered nowadays which may include: wastewater treatment and water purification coupled with sea water desalination. In this application waste water is used as a feed solution and a high saline source of water like sea water is used as a draw solution[3]. Water permeated from the feed solution to the sea water resulting in diluted sea water and concentrated waste water. Another possible application is fertigation where a concentrated fertilizer is use as a draw solution and brackish ground water as a feed solution. As water permeates, the concentrated fertilizer becomes diluted and can be used directly in irrigation.

4. Objective

Experimentally obtain the water flux values and reverse salt flux values for a commercially available membrane using deionized water as a feed solution and different concentrations of NaCl as a draw solution in order to be able to assess the overall process performance of different applications.

5. Methodology

An experimental setup was prepared in order to measure the water fluxes for different salt concentrations. Figure (3) illustrates a schematic for the setup. It includes a custom made FO cell made up of plexi glass. It has an upper section where the FS flows and a lower section where the draw solution flows separated by the membrane. Flat sheet membranes from porifera were used in all experiments. Two diaphragm pumps were used to pump the feed and draw solutions. Two pressure gauges and two flow meters were used to measure and monitor the pressure and discharge respectively. Needle valves were used to accurately adjust the pressure and flow values. A conductivity meter was used to measure the increase in feed water salinity in order to calculate the RSF. A digital balance that was connected to a computer via a digital data logger was used to measure the increase in draw solution volume to be translated into water fluxes. Each experiment was replicated at least three times to ensure the consistency of the results. The flow rates of the feed and draw solution were adjusted such that they were equal to 0.3 LPM and the pressure was adjusted such that both pressure gauges had a reading of 0.5 bars such that the differential pressure across the membrane was equal to zero. The experiment was left to run for at least one hour before taking any flux measurements to ensure that a steady state has been reached. The membrane was backwashed between any two experiments by flushing deionized water at a flow rate of 1 LPM.

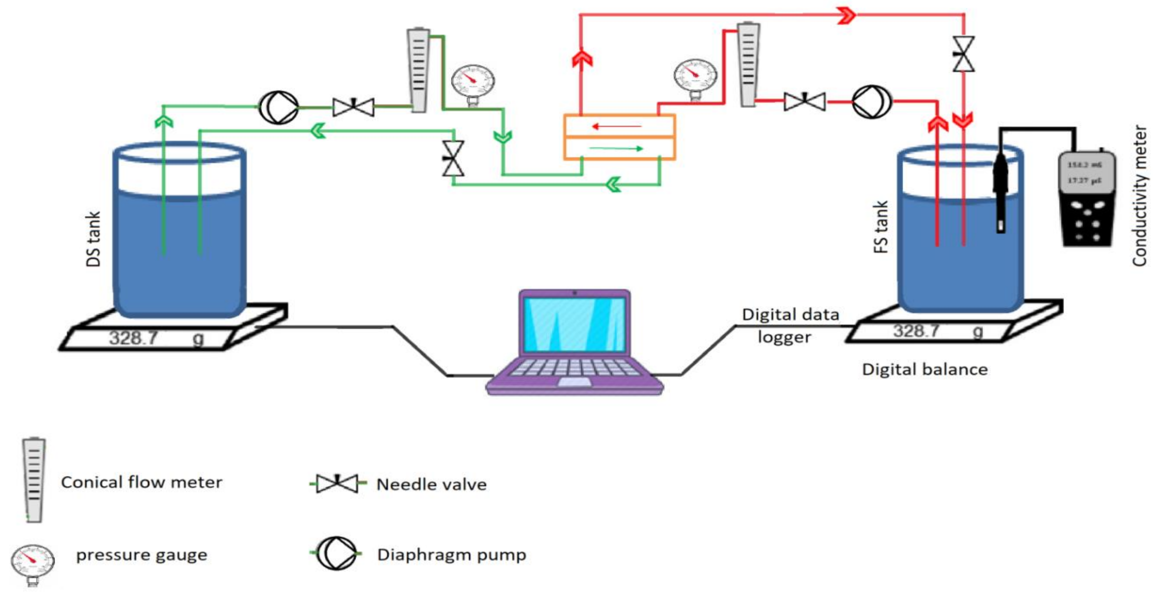

Figure 3: experimental setup

6. Results and discussions

Water flux is given as the volume of water that permeates through a unit area of the membrane in a unit time and usually expressed in LMH(liters per square meter per hour). It was found to increase logarithmically as the salt concentration increases as shown in figure (4). Increasing the salt concentration increases the osmotic pressure linearly but this did not correspond to linear increase in water flux. This behavior might be attributed to the fact that as the water flux increases, the severity of the concentration polarization increases and thus the effective differential osmotic pressure is not as high as one expected.

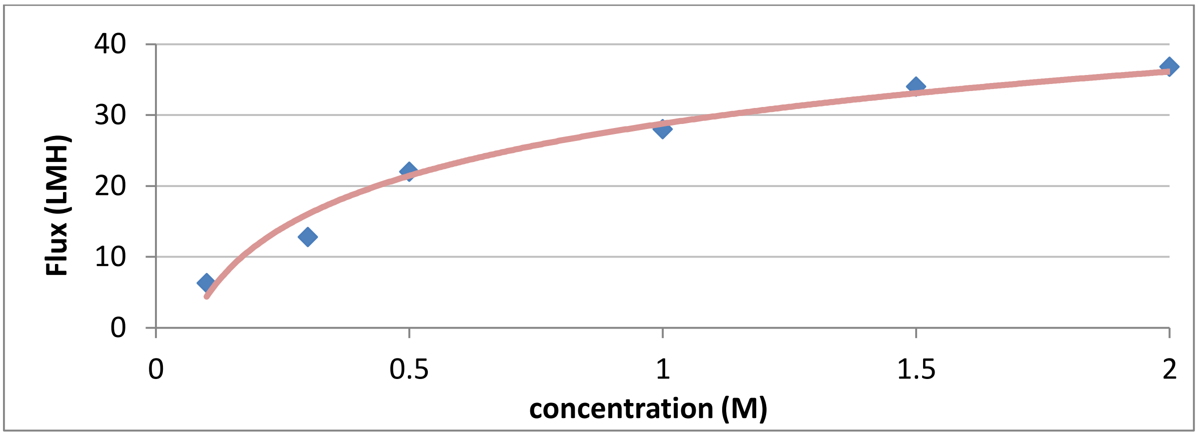

Figure 5: variation of the water flux with the salt concentration

As for the reverse salt flux, it is the mass of salt that moves from the draw solution to the feed solution per unit area of the membrane per unit time and is usually given in gmh (grams per square meter per hour). It was also found to increase logarithmically with the increase in salt concentration probably for the same reason as the water flux as shown in figure (6).

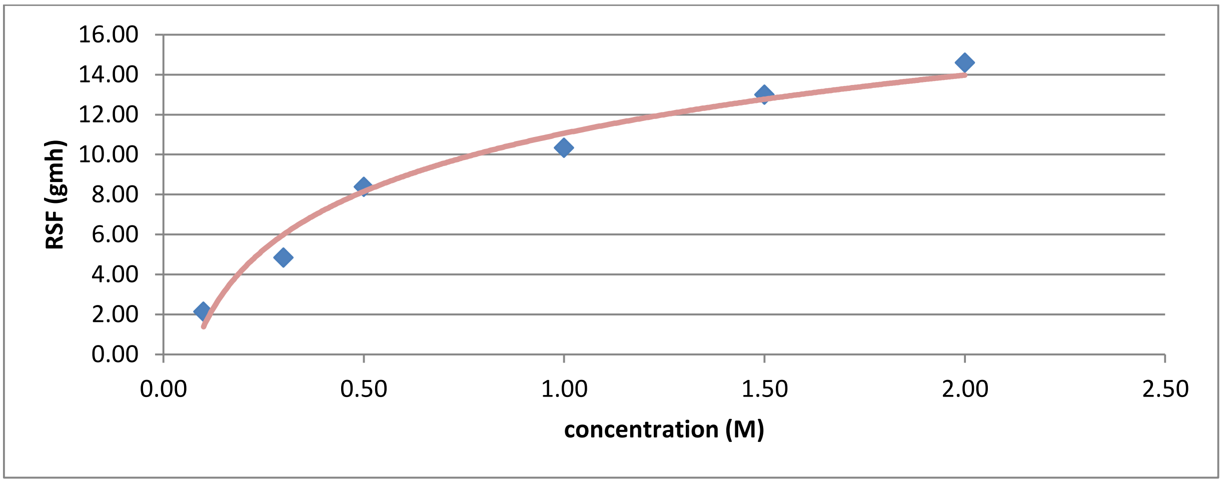

Figure 7: variation of RSF with salt concentration

Another important parameter that needs to be added is the specific reverse solute flux, which is the RSF divided by the water flux and usually expressed in g/l (gram salt per liter of water). Figure (8) shows that the SRSF remains constant regardless of the salt concentration. This is because as the salt concentration increases , the water flux and RSF increase and thus the ratio between them remains unchanged.

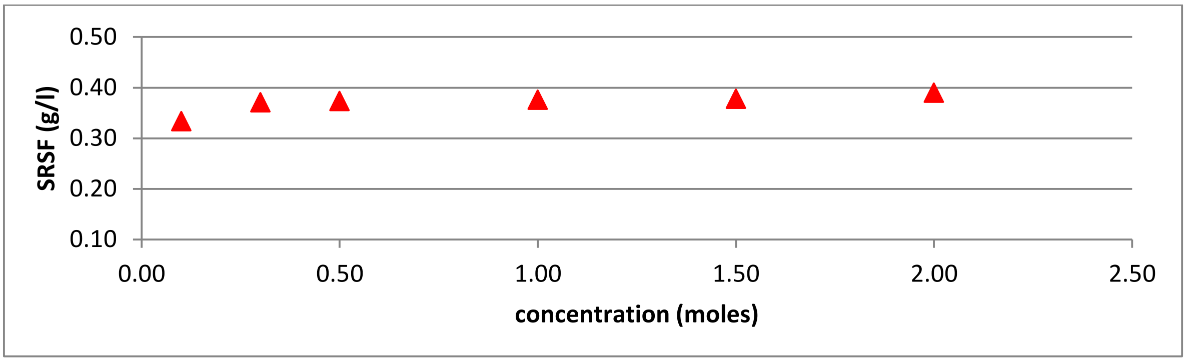

Figure 9: variation of SRSF with salt concentration

7. Conclusions

A bench scale experimental setup was performed to measure the water fluxes and reverse salt fluxes with respect to the salt concentration for the FO membranes from Porifera. Both the water flux and the reverse salt flux were found to increase logarithmically with the increase in salt concentration, but the ratio between them did not change.

8. Recommendations

Many parameters other than the salt concentration might influence the water flux and RSF values, like the cross flow rates and cross flow velocities, differential pressure across the membrane, and water temperature. Also fouling was not studied in this research. Thus more studies should be performed to investigate the change in water flux taking into account the other parameters.

9. References

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