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Development of a Multifunctional Membrane Process

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Abstract:

Historisk set har mennesket tidligere brugt flere forskellige krystalleringsmetoder. Da membran-krystallisering blev opdaget, fandt man en ny og energifavorabel metode, som kunne bruges til at forårsage overmætning i en væske - og derefter krystallering. Med nutidens fokus på mangel på vand og minimeringen af natur, der skal omlægges til industri, har en process kaldet perkrystallering (PCr) vist sig at være en mulig løsning på disse problemer. PCr sikre produktion af tørre krystaller direkte fra væsken, samt har høje produktionsrater og vand flux sammenlignet med andre kommercielle afsaltningsmetoder. I denne afhandling har PCr været testet ved brug af en polymerisk og en keramisk membran, hvori opereringskrav til disse er diskuteret. Succesfuld kontinuer produktion af NaCl og CuSO lykkedes ved brug af en keramisk membran. Faktorer som fordampningsrate (RE) og permeationsrate (RP) er blevet undersøgt. Denne afhandling fand ud af, at ratioen mellem RE og RP er meget vigtig ift. at kontrollere den samlede process og at membran egenskaber og eksperimentielle variabler er vigtige for at kontrollere denne ratio.

Development of a Multifunctional Membrane Process

Sebastian Lund Hansen

21/12/2021

Abstract. Throughout history, mankind have utilized different crystallization techniques. With the introduction of membrane crystallization a new and energetically favourable method was discovered for causing supersaturation in a solution, hence inducing crystallization. With the present focus on water scarcity and plant size reduction a novel process named percrystallization (PCr) have proved to be of great interest. PCr allows the production of dry crystals directly from solution, while having high production rates and water flux compared to commercial desalination processes. PCr was tested using a polymeric and a ceramic membrane, where multiple process requirements are discussed. Successful continuous production of dry NaCl and CuSO crystals were obtained using a ceramic membrane. Factors such as feed temperature and concentration were tested and variables as rate of evaporation (RE) and rate of permeation (RP) was discussed. The study found that the RE/RP ratio is very important in controlling the process, and membrane properties and experiment conditions are vital to be able to control this ratio.

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1 Introduction

Crystallization is an old chemical process and unit operation that has been used by mankind for thousands of years[1]. The first recorded crystallization product was salt and lead to other uses such as evaporating sugar cane juice to keep the crystals as a mean of preservation. Even today, large evaporation ponds are still being used in the production of salt from brine water[2]. However, these evaporation ponds carry certain disadvantages as high plant footprint, and they are also very climate dependent as they require high evaporation rates, low humidity etc. [2]

A breakthrough came with the introduction of membrane crystallization[4]. A multi-functional chemical process being able to separate a solution while causing supersaturation, which eventually will lead to component solidification. This allowed membrane crystallization to produce desired solids and pure solvent with relative low energy cost. The solids would solidify in the feed solution. Thus, to obtain pure crystals, the remaining feed solution would first be filtered and afterwards the crystal have to undergo a drying process to eliminate the last feed solution present with the crystals[5]. However filtering and drying processes can be skipped when introducing percrystallization (PCr).

In PCr the crystallization process takes place on the permeate side, hence the name [3]. As warm water permeates the pores it creates a thin film on the permeate surface side of the membrane , see figure 1c. The water, constituting the thin film, is then evaporated. The evaporation of the water causes a supersaturation of the dissolved crystals, which then start to precipitate on the membrane surface and drop as dry crystals due to gravitational forces[6]. The formation of the thin film is crucial to creating a continuous working process. Two important perimeters for the PCr process is the rate of permeation (RP) and rate of evaporation (RE), which are in an equilibrium determining the functioning of the process. If the RP is too high compared to the RE no film would be obtained. Instead water would flow through the membrane, not be evaporated and the crystals would never reach supersaturation and precipitate. Likewise, if the RP is too low compared to the RE no film would be obtained, which could be due to water evaporating while still in the membrane pores. Thus, the balance between RE and RP is important. [3]

So far all studies on PCr have utilized ceramic membranes. This is most likely due to an already present hydrophillic surface which easily can be modified and the fact that inorganic/ceramic membranes have been absent in the membrane distillation (MD) industry [5].

For MD, polymeric membranes are most common since they are of low production cost compared to the ceramic membranes and have initial hydrophobic surfaces [7]. Schnit et al. 2021 describe that the use of polymeric membranes in MD is sufficient in most applications, but that dealing with highly concentrated brine water, extreme chemistry and temperatures might require another membrane with better properties regarding the issue at hand [7]. Generally, ceramic membranes are regarded mechanically stronger and prove better resistance to fouling and chemical attacks compared to traditional non-modified polymeric membranes [8]. With almost endless modification possibilities of both polymeric and ceramic membranes both are interesting for studies. However, if the ceramic membrane should be introduced more commonly the benefits should outweigh the increased cost of production, otherwise the use of ceramic membrane will continue to be for the more extreme situation as mentioned earlier. [7]

In general, the literature available on PCr is limited [5][3][6][9] and as mentioned earlier all experiments so far have been using ceramic membranes with a carbon layer on the shell side. This means that the full potential for both ceramic and especially polymeric membranes in PCr have not been found. The general different properties of polymeric and ceramic have been highlighted and the low cost of polymeric membranes could prove beneficial in implementing PCr as a commercial filtration method. [10]

When discussing the usage of hydrophobic polymeric membranes in PCr the hydrophobicity must be modified in order to introduce water into the pores[11]. Since little to no literature is available on specifically wetting hydrophobic polymeric membrane to obtain properties applicable for PCr, the information on wetting in MD must be utilized. Wetting in MD is mostly referred to as a flaw to the membrane, which in turn will lead to a decrease in permeate flux and quality [11][12]. When a non-wetting solution is used as a feed solution the working principle of MD is the fact that the capillary pressure originating from the surface tension interaction between the membrane and feed solution prevents the liquid from entering the pores [13]. In hydrophobic membranes wetting occurs primarily when the liquid entry pressure (LEP) is reached. The LEP is defined as the amount of pressure, which is required for the solution to enter the dry pores of the membrane. Based on the Young-Laplace equation, the calculation of LEP is given in eq.1.[11][13]

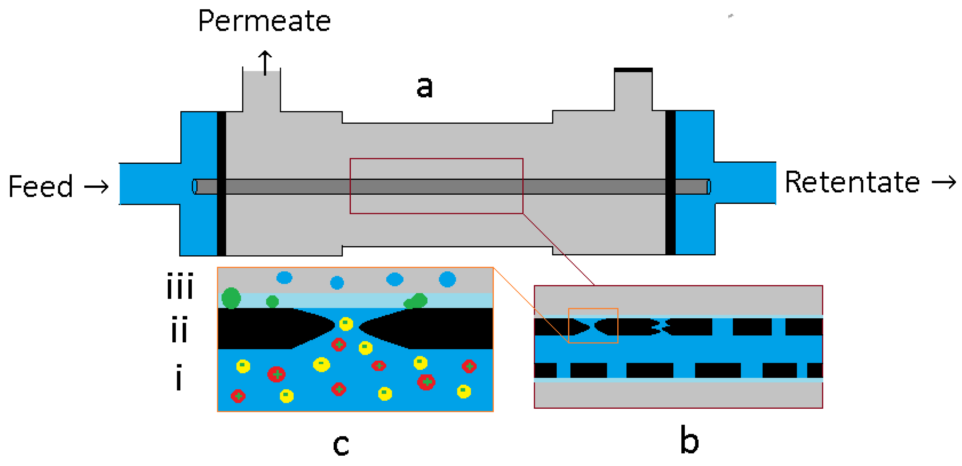


Figure 1: Illustration of: a) hollow fiber membrane module design. b) Closeup of the pores of the membrane allowing permeation of water to the thin film. c) Focus on one single pore, which has been divided into three sections. i, the feed stream containing dissolved salt ions (red and yellow circles). ii, the ions are carried with water through the pores into the permeate surface side of the membrane. iii, the salt (green circles) precipitates in the thin film due to supersaturation, as the water (blue circles) is simultaneously evaporated. Made with inspiration from [3].

$$LEP = \frac{-2B\gamma_l cos(\theta)}{r_{max}} \tag{1}$$

where B is the pore geometry coefficient ranging from 0 to 1 (1=complete cylindrical pores), γ_l is the surface tension of the liquid, θ is the contact angle measured on the feed side of the membrane and r_{max} is the maximum pore size of the membrane [14]. Eq. 1 is what explains the idea behind inducing wetting in a hydrophobic polymeric membrane for PCr application. By using a low surface tension (LST) solution, in regard to water, as a feed solution the LEP will lowered and at a certain pressure applied liquid will enter the pores and initially wet the pore openings. This will cause a local hydrophilicity which eventually will lead to continuous water bridging[13].

Choosing different LST liquids can affect the type of achieved wetting[11]. This has been shown for surfactants and alcohols[12]. Pretreating with an alcohol causes a more abrupt full wetting of the membrane, which is not desired for reaching an applicable permeation rate in correspondence to the rate of evaporation. Pretreating with a surfactant causes a more dynamic partial wetting of the membrane. The driving force for wetting with surfactant is more dependent on the adsorption onto membrane pore walls, convection - to replenish more surfactants at the wetting frontier and the bulk concentration of surfactant which will be higher than the concentration at the wetting frontier. [12]

The objective of the thesis is to study the novel process of PCr using both ceramic and polymeric membranes. Additionally, operating parameters, which are known to have an affect on MD processes, will be tested to discover the overall effect of those paramters.

2 Materials and Methods

2.1 Membrane assembly and setup

Membrane modules were constructed using plexiglass and Polyvinylchloride tube as shown in figure 1. The setup for the system is shown in figure 2. For explanation of the abbreviation, check the figure caption. The feed solution is placed in a graduated cylinder, from which a flux is calculated. The feed solution is carried through metal coils in a heated bath (Grant Struers kebolab) using a peristaltic pump(Cole-Parmer Masterflex). The pressure and temperature is monitored at the inlet and outlet of the membrane using manometers and thermometers. The valve placed at the membrane outlet was used to create hydraulic pressure if needed. Vapor permeate is collected in a cold trap which is assisted by a vacuum pump(vacumbrand,PC 3001 Vario). The manometer on this side is placed to monitor the low pressure created by the vacuum pump. The cold trap is a Büchner flask in a box with ice.

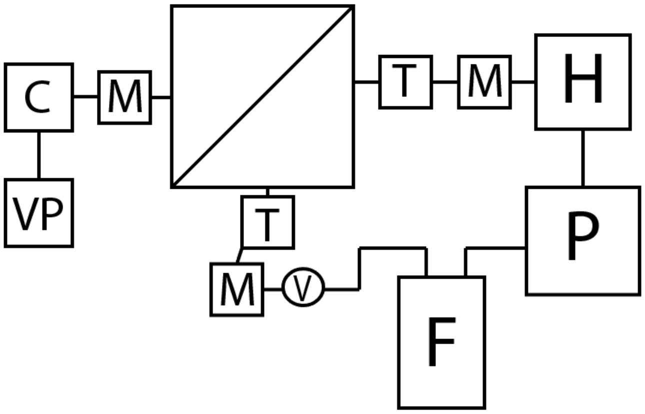


Figure 2: Experimental setup which includes a feed reservoir (F), peristaltic pump (P), heated bath (H), manometers (M), thermometers (T), valve (V), cold trap (C) and a vacuum pump (VP).

2.2 Polypropylene membrane

For polymeric hollow fiber membrane Polypropylene (PP) Accurel s6/2 (Membrana) were used. These membranes have an overall porosity of 73% and LEP of 1.4 bar. As described earlier, for the polymeric membranes, wetting had to be induced to create permeation. LST solutions were used with varying TMP using both hydraulic pressure, caused by closing the valve, and applied vacuum -0.95 bar. To activate PP membranes isopropanol alcohol (IPA)(VWR) and Triton x-100™(MERCK) was used in a range from $0.5 - 8wt\%$ and $50 - 500ppm$, respectively. Fx a concentration of 1 wt% of IPA was used with pressure increasing to 3.5 TMP or until permeation was observed. Properties of the PP membrane are listed in table 1.

2.3 Alumina doped silica membrane

For the ceramic membrane a tubular α-Aluminia support with a γ-alumina intermediate(Pervatech B.V) was used. The support had been dip coated during an earlier project on the inside with a sol based on TEOS, ethanol, nitric acid with added CTAB and aluminium isopropoxide. For more in depth synthesis and membrane fabrication see Xianzheng Ma et al. 2019[15]. For PCr analysis $NaCl$(VWR) and $Cu(2)SO_4(H_2O)_5$ (Prolabo) were used. Initially the copper sulfate was used to have a clear visual indicator that crystals were forming on the membrane surface, however this was found to be sufficiently clear with NaCl, thus NaCl was used from that point and on. Properties of the ADSM are provided in table 1. NaCl flux was calculated by removing the generated salt from the system and quantifying the mass by a standard curve of concentration against conductivity. Eventually, the system was flushed with water on both feed and shell side between each experiment to obtain as consistent results as possible.

Table 1: Membrane Characteristics of PP Accurel 6/s2 and the aluminia-doped silica membranes

Membrane Characteristics	PP Accurel 6/s2	Alumina-doped Silica
Outer diameter (mm)	2.25	10
Inner diameter (mm)	1.80	7
Thickness (mm)	0.45	3
Average Pore Size	0.2 μm	1.1 nm
Contact Angle (°)	98	94

In this thesis the aim is to analyze the requirement and working principle of PCr. Is it possible to obtain a continuous PCr process with polymeric membrane by introducing wetting with a LST liquid? Is the carbon layer a necessity for ceramic membranes to successfully carry out PCr? How are different working parameters affecting the process?

3 Results and Discussion

3.1 Polypropylene membrane

For the PP membrane there was a hypothesis that using a LST liquid in the activation of the membrane would be successful in inducing wetting and thus permeation. It was also theorized that by changing the surface tension of the activation solution, one could control that the RP does not exceed the RE. This had been proven by a semester group on site beforehand. Though, it should be stated that the PCr process only succeeded once and that producing consistent results was unsuccessful. Recreating this, proved to be problematic. As stated earlier, wetting with an alcohol occurs in a matter of seconds [11], so the ideal wetting grade would be hard to achieve. This was tried to overcome by using another type of LST activation liquid, a surfactant. This should cause a more dynamic wetting due to the bridge building anology, that surfactant molecules had to be transported to the wetting frontier [12]. Presumably, this should increase the span of the ideal LST liquid concentration and TMP combination. Nevertheless, attempts were made using many combinations of TMP and IPA/Triton x-100™ concentration. The properties of the activated membrane would always be either too high or too low RE/RP ratio, thus a film for PCr would not be made. Any RP obtained was always too high for the vacuum setup to overcome. Thus one should discuss the relevance of polymeric membranes in future works with PCr, with regards to the ceramic membrane that are more hydrophilic in general and have a larger pore size resulting in permeation which was applicable for PCr [6]. With many modification of PP and other polymeric membranes [16][17] - one should not disregard polymeric membranes yet, however physically inducing wetting using a LST liquid as a mean of achieving permeation without changing the hydrophobicity or pore size, should be omitted. Instead a modification of the hydrophobicity and pore size should be the focus, with regard to the observation made in this thesis.

3.2 Alumina-doped silica membrane

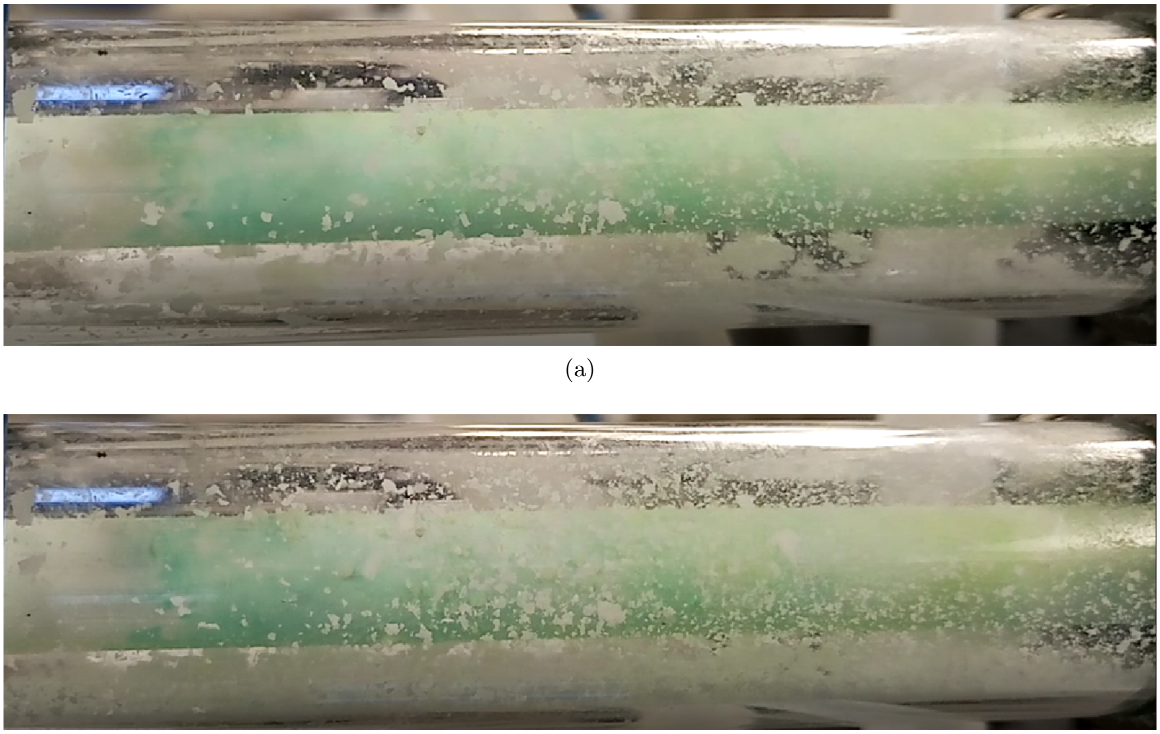
Figure 3: Percrystalisation experiment with Copper sulfate.

Early in the process it was discovered that permeation happened for the alumina-doped silica membrane (ADSM) at just 0.95 bar TMP using DI. This was obtained by only using vacuum pump, thus no hydraulic pressure induced by the valve was needed. PCr experiments were carried out, having a feed inlet temperature of 50 °C, with Copper(2)sulfate initially so any crystal formation on the surface would be visible. The PCr process occurred, blue crystals were forming on the membrane, though most of the crystals were ejected from the surface to the plexi glass surface, as seen in figure 3, at a high speed probably due to applied vacuum.

At this moment the PCr process did not occur uniformly at start. From figure 3 some crystals are observed on the membrane surface to the left and right of the arm keeping the membrane in place. This might suggest that the doping of the ADSM was not homogeneous and that possibly a larger pore size is present in the middle of the membrane around the part covered in blue crystals. This is in compliance with the pore size distribution analysis carried out by Xianzheng Ma et al. 2019 [15], in which there are two pore width groups. One is centered around the pore width of 0.75 nm with the other being centered around 1.50 nm.

With the knowledge that dry crystals are forming at given conditions, a change was made from $CuSO^4$ to NaCl to minimize material cost and waste production. At the same conditions another experiment with NaCl was carried out. This proved to be sufficient visually and a higher rate of crystal formation was observed. The PCr process is shown at two different time steps in figure 4. In figure 4a at 30 seconds a minor layer of crystals are collected at the bottom of the plexi glass tube and at 180 seconds (4b) the height of the crystal layer has reached the membrane. Once again there is only a small amount of crystal formation on the membrane and most of the crystals are instantly discharged to the sides and bottom of the plexi glass. In this experiment a more uniform PCr takes place, which may disprove the fact that a larger pore size is present in the middle, as observed with the CuSO experiment, but more likely suggest that a alternating path through the pores may affect which pores get filled and which do not.

This specific experiment with NaCl was a breakthrough in the experimentation, since this was the first time dry crystals was obtained continuously and uniformly. The product can be seen in figure 5.



(a)

(b)

Figure 4: NaCl Precrystalization with a 17.5 wt% NaCl solution at 50 °C using 0.95 TMP. Pictures are from 30 (a) and 180 (b) seconds

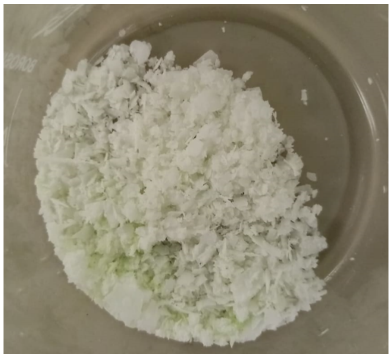
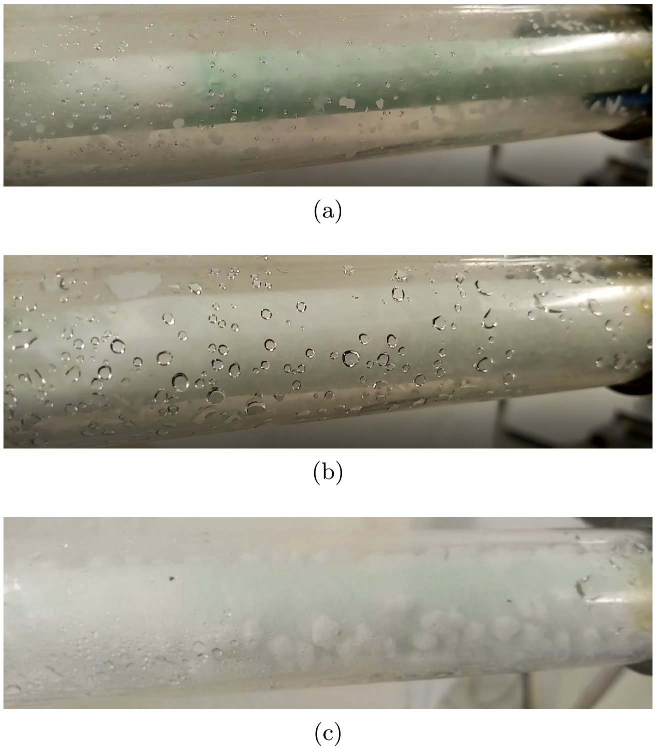


Figure 5: Product of NaCl precrystalization with a 17.5 wt% NaCl solution at 50 °C using 0.95 TMP.

A slight green/yellow color can be observed in the bottom left of the sample which is the reaction of NaCl and some CuSO from previous experiments which still was present in the system. Reproducing this experiment never was successful. At the same operating condition, issues as too high RP, water condensing on the glass surface and different kind of PCr outcomes were observed. One of the contributing factors to variation in PCr results is deemed to be an inconsistency in resetting the system after an experiment. Initially, it was found that water flushing the system on both shell and feed side and drying the system at 60 °C for 14-18h proved to give relatively consistent runs for a 17.5 wt% NaCl solution at 70 °C with a water flux at $19.85 \pm 1.5 kg/(m^2 * h)$ over four repetitions. However, this was found too time consuming since realistically only one experiment could be carried out per day. Thus, it was attempted to do water flushing and keep it wet overnight. This proved to be very beneficial achieving a water flux of $26.81 \pm 1.88 kg/(m^2 * h)$ over four repetitions. Even though this resulted in a higher and consistent water flux it did not fix an issue where different types of PCr would occur. The first type of PCr is the one shown in figure 4, where crystals are formed at the shell surface of the membrane and discharged to the glass surface. Another type is where minimal crystals are discharged to the glass surface and a crust is formed around the membrane which is increasing in size over time as illustrated in figure 6.



(a)

(b)

(c)

Figure 6: NaCl Precrystalization with a 17.5 wt% NaCl solution at 70 °C using 0.95 TMP. Pictures are from 1 (a), 45 (b) and 60 minutes (different experiment than a and b) (c).

The crust is forming uniformly across the membrane. As the crystal layer expands further it eventually builds off the membrane shell side surface, which results in the visual observed in figure 6b. Eventually, the crystal crust formation continues in a specific points resulting in blunt expansion points, see figure 6c. This shows that the position of the thin film has changed over time as the diameter of the crust increases. The position of the thin film could be reason for the two different outcomes. In figure 7 the composition of a ceramic membrane is shown.

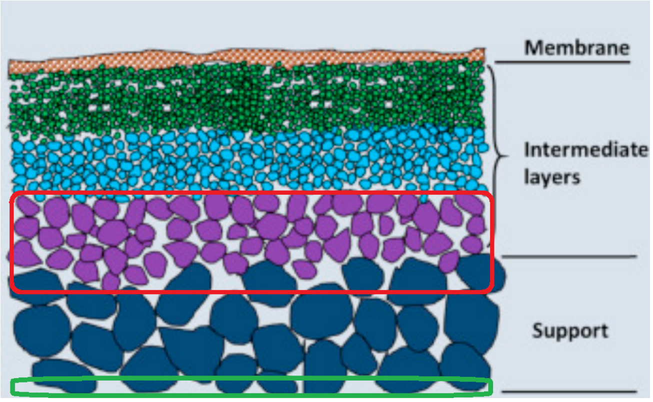


Figure 7: Overview of the composition of a ceramic membrane. The ideal thin film position is highlighted in green - with the less ideal being highlighted in red. Edit of [18].

Furthermore the ideal and the not ideal position of liquid/vapor interface are highlighted in green and red, respectively. As mentioned, in the ideal experiment liquid travels to the shell side of the membrane where the water is evaporated. However, if the RE/RP ratio is too high crystallization could occur in the support layer. This is plausible what happens during the crust formation. Over time the liquid/vapor interface is moved further through the support layer and no discharge of crystals is observed since all crystals are in a crystal lattice which promotes a stronger connection, which is not overcome by the gravitational forces. This initial nucleation and crystal formation could also promote a more rapid crystallization in the support layer by secondary nucleation [19]. If the position the liquid/vapor interface is in the green section of figure 7 the crystals are expected to discharge from the membrane surface due to the combination of vacuum and gravitational forces, which presumably would overcome the forces keeping the crystal at the surface. This crust formation was also obtained by C. Zhang et al 2021, where a growing layer would form on the membranes surface during PCr [9]. As mentioned, the desired dry quality of the crystals was challenged by the formation of droplets on the glass surface, as seen on figure 6b. Vapor from the membrane surface condenses on the glass due to vacuum system not being sufficient. This could be overcome for future work by either modifying the setup or coating the glass interior. Anyhow, this problem caused dry discharged crystals to absorb water and appear as sleet as shown in figure 8.

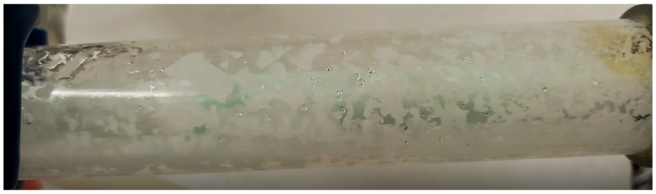


Figure 8: The NaCl crystal appearing as sleet due to water condensing on the glass surface

As the feed temperature strongly affects the LEP [14] and the vapor pressure of the feed solution [20], it is relevant to study how the feed temperature affects the PCr process. At increasing temperature, the water and NaCl flux have been investigated and the results are shown in figure 9.

As the temperature of the feed solution is increased so is the water flux for both DI water and a 17.5 wt% NaCl solution. However, the DI water has a significant higher water flux than for the NaCl solution. This was expected, as it is known that adding salt to water both increases the surface tension of the liquid [21] and decreasing the water vapor pressure [22] - two factors which could affect PCr process. Likewise is the NaCl flux also increased at higher temperatures of feed solution. As the PCr process in general is still a novel process, it has not been discussed how and why temperature affects the NaCl flux. One could argue that it makes sense, while comparing it to vacuum membrane distillation (VMD), which is what the process is nearest related to. In VMD one would achieve an increased flux as temperature is increased due to the raised vapor pressure[20], however increasing the vapour pressure of water, thus the RE, in PCr does not increase the NaCl flux directly as a constant convectional flux is assumed to be present in a continuous system. The NaCl flux should be more dependant on the RP. The role of evaporation in PCr is only to secure that no liquid water is permeating all the way through the membrane making the crystals wet. Hence, when assessing the reason for increased NaCl flux with increasing feed temperature, the focus should be on the factors contributing to a higher RP such as lower LEP [14].

A factor which is relevant to study for PCr is the concentration of the feed solution [20]. With a feed concentration range of 0 to 17.5 wt% the corresponding water and NaCl flux was investigated and the results are shown in figure 10. A decrease in water flux is observed with increasing NaCl-concentration. This is in compliance with the general understanding of the feed salt concentration's effect on water flux as increasing the concentration introduces more non volatile solutes and lower the activity coefficient of water [20]. However this observation was not in compliance with what was observed by R. Madsen et al. [5], where an increase in salt concentration from 12.5 to 20 wt% caused no significant change in flux. With the drop of water flux, it is relevant to discuss why no liquid is permeating the membrane causing undesirable wet crystals. One reason could be that the increase of salt concentration is resulting in a lower RP, as the contact angle of water is increasing with salt concentration [23], hence increasing the LEP. Another one could be that the viscosity of the solution increases which limits the permeation of the pores [5]. In this thesis a linear increase in NaCl flux was observed with increasing sodium chloride solu-

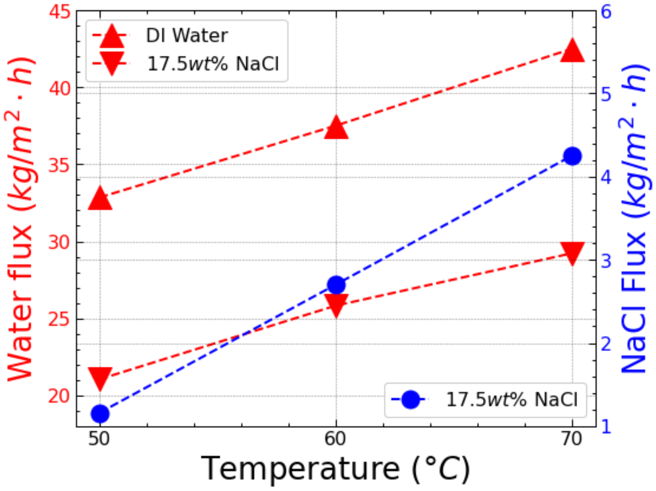


Figure 9: Water flux for DI water and a 17.5 $wt\%$ NaCl solution and NaCl flux of a 17.5 $wt\%$ NaCl solution at different temperatures

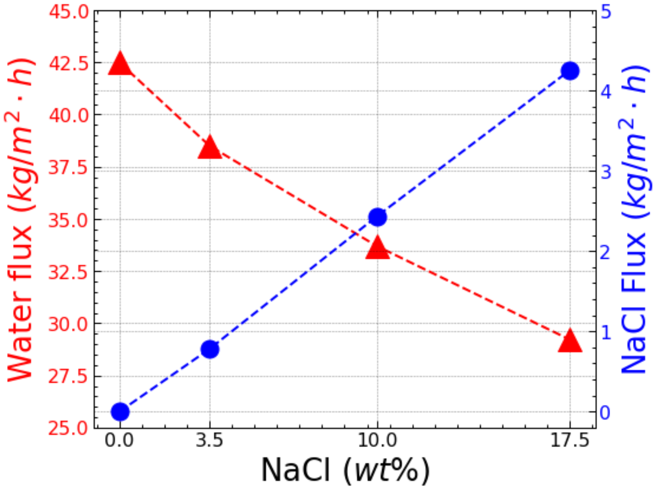


Figure 10: Water and NaCl flux at 70 °C at varying NaCl concentration

tion. This means that despite the decreasing water flux the increase in feed concentration dominated the overall NaCl flux.

Another relevant factor for characterizing the membrane is the temperature drop with increasing length of membrane, which has been highlighted by Ji Qi et. al 2020 [24]. They found that increasing the active length of the membrane from 100 to 200 mm, they experienced a 5% drop in water flux. With an effective membrane length of 30 mm, Rasmus et. al 2018 [6] would not experience the same temperature and performance drop as with the dimension of the ADSM, which had an effective length of 210 mm. The lenght of the ADSM caused a drop of 5, 5-7 and 8-9 °C over the membrane for 50, 60 and 70 °C experiments - measured at the outlet of the membrane module. This - in combination operating conditions and different membrane material properties, would contribute to why the ADSM prove similar results to the sucrose dip coated.

Similar experiments were carried out by R. Madsen et al. 2018 on α-alumina tubes dip coated in sucrose. The properties of the achieved membrane was a pore size of 0.1 μm and a contact angle of 107-118°depending on carbonisation temperature [6]. With the assumption that eq 1 is defining for the water flux of the membrane, the ADSM have a much smaller pore size, thus it should be much harder for liquid to permeate to the shell surface side of the membrane. Following that, R. Madsen reports higher fluxes and better salt production rates. They find that a higher contact angle results in a higher water flux which they state is in agreement which what is observed for Direct contcat and VMD [20], but with regards to PCr an increase in contact angle should not increase the water flux. They also state that increasing the water flux evaporated at the liquid/vapor interface increases the NaCl flux. This conclusion has been challenged in this thesis, in which the NaCl flux is deemed to be more dependent on RP than RE. If it is assumed that the RP is constant and not affected by RE, the only thing RE does is shift the position of the liquid/vapor interface. This goes back to the basic assumptions that if $RE > RP$ eventually the liquid/vapor interface will shift so far towards the feed membrane surface that the PCr process becomes VMD and if the $RE < RP$ then one eventually would obtain a fully wetted membrane and liquid permeation. Still, the novelty of this process must be considered. To fully understand the effect of the RE/RP ratio and when this process can and can not be compared to VMD or other traditional MD types, more studies have to be carried out.

As mentioned, more work is heavily required to better understand the PCr process. Many factors which affect the VMD process also affect the PCr process.This includes membrane material, feed side membrane surface chemistry, feed temperature, membrane length, TMP, vacuum pressure, feed concentration, position of liquid/vapor interface etc. These parameters are all easily tested, however obtaining a functioning PCr process in the first place is what might prove to be biggest task when studying the process. The reproducibility of PCr studies have so far only been done for the sugar carbonised α-alumina substrate[5][6][3], for which there have been great success in controlling the position of the liquid/vapor interface securing continuous ejection of crystal into the vapor chamber. The introduction of a carbon layer on the shell side membrane surface is so far still the most promising method for designing a ceramic membrane for PCr. This is probably also why Rasmus et al. decided to not change the modification over the course of three studies. However, the studies carried out by R. Madsen et al. do not explain the specific role/significance of the carbon layer and whether it is replaceable with some other material.

4 Conclusion

The novel process of PCr have been studied using both polymeric and ceramic membranes. The polymeric membrane still has unexplored potential, however no success was achieved using a physical activation of inducing wetting with a LST liquid. The PCr process was successfully carried out using a ceramic membrane, ADSM. The already present hydrophillic properties of a ceramic membrane proved to be beneficial for executing the PCr experiments. PCr experiments was carried out with both CuSO and NaCl, however in depth studies was only carried out with NaCl. Two types of PCr outcomes was discovered - a continuous crust formation surrounding the membrane and a continuous discharge of dry crystals to the glass surface. Important subjects such as position of liquid/vapor interface, RE and RP have been discussed in relation to observation and data. Using a 17.5 wt% NaCl solution a water flux of $26.81 \pm 1.88 kg/(m^2 \cdot h)$ was achieved and a NaCl flux of $4.25 \pm 0.58 kg/(m^2 \cdot h)$. Further work is needed to get a better understanding of the PCr process and the effect of a carbon shell side layer conducted by R. Madsen et al. Additionally, introducing hydrophilicity into a polymeric membrane still could prove to provide a cost effective alternative to the more expensive ceramic membranes.

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