Performance analysis of Air Gap Membrane Distillation: Comparison of PTFE membranes

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Abstract

Membrane Distillation (MD) is a very promising new technology which can be coupled with renewable energies and/or waste heat to produce pure water at a low-cost. MD is extremely dependent upon the performance of the membrane, as it dictates the mass transfer, the heat transfer and the long-term application. Unfortunately, there are no commercially produced MD-specific membranes at this point in time. This project aims at finding correlations between membrane characteristics and their performances in order to define the optimal morphologies and operating conditions for a MD-specific membrane. To do so, the characteristics of 3 PTFE membranes initially designed for MF were determined through porosity measurements and microscopic imaging, while their performances were evaluated by measuring the air permeability and by testing them on an AGMD bench-scale unit.

It was found that the most desirable characteristics for a membrane with a high flux are a film with large porosity, low tortuosity, a small thickness with a resistance to compaction and that has not been subjected to thickness altering processes. Moreover, the surface pore sizes need to be small enough to avoid surface wetting, and the backing layer should not restrict the vapor flow in a significant way and should possess large open areas.

As the feed water temperature and/or the flow rate rises, the flux increases and the energy requirement decreases, this means that one should ideally aim for the highest possible operating conditions which requires larger costs. Therefore it is necessary to find a cost effective solution for each application.

The results show that, for comparative purposes, Gurley values are good indicators of a membrane’s overall performance in MD, despite the fact that it does not always accurately predict it. It has also been found that membrane specifications provided by manufacturers are generally only approximations, and should therefore not be used as very precise data for comparing membranes.

Keywords: Membrane distillation, air gap, flux, PTFE, backing, morphology, performance, Gurley.
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1 Introduction

1.1 Water issues

Even though only 1% of all of earth’s water is fresh water, which can theoretically satisfy the world’s demand, about one eights of the population lacks access to safe water supplies. Water demand has increased by a factor of 4 in the past 50 years, and is still soaring at a rate twice as big as the population increase. It is imperative that actions are taken now to safeguard the future of our planet.

There are different ways of dealing with this problem, such as retaining water (storage, conservation, rain harvesting), decreasing the demand and wastage, recycling and reusing water and desalinating sea water (which is 97% of the earth’s water supply). A disadvantage of the last two options is their relatively high energy requirements. There is a strong link between water and energy shortages, which cannot be ignored.

A critical step for safeguarding our future is the research and development of new efficient and cost-effective technologies to produce clean water with a focus on reducing the energy requirements.

1.2 Membrane Distillation

The Membrane Distillation (MD) process is an emerging technology for water purification which utilizes the driving force of a temperature gradient to transport vapor molecules through a microporous hydrophobic membrane. After passing through the latter, they are condensed on the other side. Theoretically, the combination of the hydro-repellent characteristics of the membrane and the driving force allows the complete rejection of non-volatile solutes.

1.2.1 MD configurations

There are 4 main types of MD configurations (Fig. 1) that have been developed.

![Fig. 1. MD configurations (M.S. El-Bourawi et al, 2006)](image)

Sweeping Gas Membrane Distillation (SGMD) consists in providing a cold inert gas that sweeps the permeate side of the membrane. This flow carries the vapor molecule away from the module to a condenser. The Vacuum Membrane Distillation (VMD) configuration is similar to the SGMD setup except that it uses a vacuum to transport the vapor molecules from the feed side to the condenser.

The most commonly used configuration is Direct Contact Membrane Distillation (DCMD) due to its simple design. In this setup, the membrane is in constant contact with the hot feed solution on one side,
and the cold permeate on the other. Both feeds are flown tangentially to the membrane. This means that the vapor is condensed in the cold feed.

In the Air-Gap Membrane Distillation (AGMD) configuration, a stagnant air gap is placed on the cold side between the membrane and a condensation surface. The latter is cooled by a constant flow of cold water. In this configuration, the vapor flows past the membrane to be condensed against the cool surface. Compared to DCMD, AGMD provides lower energy losses but a lower flux too.

According to El-Bourawi et al (2006), each configuration is better suited for specific applications. DCMD is best suited for applications when non-volatile components are considered, as well as when the major permeate component is water. AGMD, however, can be applied to all DCMD applications, but also to remove trace volatile components. VMD and SGMD are best suited for the removal volatile organic components from aqueous solutions.

DCMD is the configuration that has been the most studied. About 64% of articles published are on DCMD, while only 17% are on AGMD, 14% on VMD and 5% on SGMD (Li et al, 2008). There is clearly a need for more research to be done on AGMD.

1.2.2 Brief history of MD

MD made its debut in the early 1960s when, on June 3\textsuperscript{rd} 1963, Bodell filed the first patent (Bodell, 1963). It was only 4 years later that the first MD article was published by Findley (1967). The latter discussed in his article the most suitable membrane characteristics for use in MD (DCMD in his case) and mentioned that “Calculations indicate possible economical performance, especially at high temperatures, if high temperature, long life and low cost membrane are obtainable.” Therefore, in 1967, the potential use of MD at an industrial was considered to be achievable. In 1968, a new patent from Bodell was made, giving birth to SGMD (with a tubular membrane module) as well as suggesting the foundations for VMD. The SGMD design was mainly created to provide new and innovative ways for the desalination of seawater. A year later, Finley and co-authors (Findley et al, 1969) published an article about the relations of heat and mass transfer from the evaporation of a hot salt solution through a hydrophobic porous membrane to a condensing surface.

After this short boom of interest in MD, a decline appeared due to the low rate of production of clean water compared to Reverse Osmosis. However, in the 1970s, Rodgers (1972, 1974) presented in a patent a new DCMD design using a stack of flat-sheet membranes. Furthermore, he mentions that the most suitable materials for MD were those that could be formed and/or treated into microporous membranes with a high porosity, uniform pore size distribution and good hydrophobicity. Interest in MD quickly rose again in the early 1980s when new membranes with better suited characteristic for the application became available. Emphasis was put on improving the thermal MD process and the designs to produce a continuous stream of clean water at a higher flow rate over a long period of time. Unfortunately, during this period, the studies were not done with an industrial interest, rather a more academic one. Moreover, W.T. Hanbury and T. Hodgkiess (1985) stated that MD would not become competitive for seawater desalination unless the prices of the membranes are “reduced by at least an order of magnitude”, and/or a “much higher distillation heat transfer coefficients” is achieved. They concluded by stating that using MD for desalination based on PTFE membranes is “unlikely to be economic”.

The inefficiencies of MD during the first part of its development have been enough to persuade the industries of its lack of potential. By not being considered as economically viable, its research and development have been hindered. This is why most membranes used today in MD applications were designed for microfiltration purposes. Therefore, to increase the productivity and efficiency of MD, membranes specifically designed for MD have to be created.
1.2.3 MD application

MD is increasingly being considered as a viable substitute to other membrane technologies. The advantages of using MD are its operating conditions (low temperature and pressure), its 100% theoretical removal of non-volatile solutes, its less demanding mechanical properties of the membrane, and its ability to use waste heat or renewable energies. MD has been successfully tested in various applications, such as desalination, environmental/waste cleanup, water reuse and in the food and chemical industries.

The efficiency and long-term performance of MD can be hindered by various factors, such as fouling, scaling, membrane decay and wetting as well as temperature and concentration polarization. As the membrane is the keystone of this process, the overall performance depends mainly on it. Therefore, one way of increasing the efficiency of MD is by optimizing the membranes’ characteristics and operating conditions to achieve maximum flux.
2 Background material

2.1 Membrane overview

For a membrane to be adequate for MD applications, it must have at least one hydrophobic layer and must be porous throughout. Some newly developed membranes combine hydrophobic and hydrophilic layers to increase its overall performance, however only hydrophobic membranes are used and considered in this thesis. Moreover, the membrane surface contacting the feed solution should be made of a material of high fouling resistance coupled with a long life and stable performance. The major component of the feed water typically used in MD is water, therefore the membrane must be made of low surface energy polymers or inorganic materials in order to be hydrophobic.

2.1.1 Microfiltration membranes

Most membranes used today for MD applications were initially designed for Microfiltration (MF) applications. MF is a low-pressure membrane process, used to separate most microorganisms (bacteria) as well as colloidal and suspended particles from an aqueous solution by means of a semi-permeable membrane with a pore size between 0.05 and 5 µm. Dissolved material and some suspended solids are not retained by MF.

There are two types of MF membranes classified either as “tortuous pore” (TP) or “capillary pore” (CP). The former resembles a sponge with a network of interconnecting tortuous pores, whereas the latter is composed of straight through cylindrical capillaries. As opposed to TP, CP membranes have smaller thicknesses, very low porosity, but they have the advantage of providing precise pore size measurements directly with a Scanning Electron Microscope (SEM) (Porter, 1990). TP membranes are the most used nowadays.

According to Wikol et al (2007) MF membranes are very often designed for air filtration which happens in two parts: surface and depth filtration. Surface filtration prevents particles from getting past the surface of the membrane, while depth filtration consists in trapping particles inside the bulk. The average pore size and shape of the surface is often designed according to the application.

2.1.2 Membrane material and production

The analyzed membranes in this thesis all have films made of Polytetrafluoroethylene (PTFE) with a backing layer made of Polypropylene (PP).

PTFE, also known as “Teflon” or “Fluon”, is a very well known fluoropolymer for its chemical resistance, thermal stability, and hydrophobicity. Those characteristics are due to its chemical structure. PTFE is solely composed of carbon atoms, forming a straight backbone, and fluorine atoms, bonded to the carbon in a uniform helical sheath (Fig. 2). The presence of Fluorine atoms in this evenly distributed shape protects the carbon backbone, while making it nonpolar and nonreactive. Furthermore, the carbon to carbon bonds and the carbon to fluorine bonds are extremely strong. The combination of those characteristics provides an extremely inert and thermally stable polymer which makes it difficult for anything to bond to it. As fluorine is the most electronegative, its atoms do not share electrons with each other, thus giving PTFE a low surface free energy. This makes PTFE very suitable for MD.
The PTFE films are laminated with Polypropylene (PP) for structural reinforcement which can be woven, non-woven or shaped to a specific geometry like scrims (Zhang et al, 2010). PP is a low density thermoplastic polymer which has an excellent resistance to stress, a high resistant to cracking and high operational temperatures. It also has a high chemical resistance, and is easy to produce. Those characteristics make it a good choice for structural reinforcement to membranes.

PTFE MF membranes are typically produced by first mixing the PTFE fine powder with an oil lubricant to create a paste which is then compressed to create a void free cylindrical perform ready for the extrusion process. The extrudate is then rolled and stretched and finally dried to remove the lubricant.

The stretching process varies according to the membrane pore size requirements. However, this process also depends on the extrusion step, as the “extrudate exhibits position-dependent property variation” (Huang et al, 2008) due to the different local pressures applied to the perform, which may influence the pore size distribution in the affected areas. A stretched PTFE microporous membrane is often referred to as “expanded PTFE”, or ePTFE.

The porous structure of ePTFE membranes (Fig. 3) is characterized by nodes, which are essentially raw dispersed particles of PTFE material, that are interconnected by fibrils (Wikol et al, 2007). The size, shape and orientation of the nodes (Fig. 4) can be controlled by the manufacturing process parameters. It is important to note that, generally speaking, MF membranes have a somewhat narrow pore size distribution.

![Chemical structure of PTFE](image1.png)

*Fig. 2. Chemical structure of PTFE (Wikol et al, 2007)*

![Structure of stretched ePTFE membranes](image2.png)

*Fig. 3. Structure of stretched ePTFE membranes*
Manufactures have different patented heat treatment methods to adapt the stretched membranes to specific applications. For example, Gore patented a technique (1984) in which it stacks a number of sheets of the extrudate which are then generally calendered before the stretching process. This increases the strength of the final product. Another Gore patent (1995) consists in knurling the sheet before expanding it to produce a high porosity without decreasing the tensile strength. A common Gore technique is to sinter the membranes after expansion. The sheet is kept in its expanded form while raising its temperature approximately to its melting point.

Donaldson patented a technique (2007) in which the membrane is exposed to heat and pressure for a predefined amount of time in order to improve its dimensional stability. This process shrinks the membrane to a certain degree due to its exposure to high temperatures and pressure.

Those techniques, and others, can be used to modify the surface of the membrane for specific applications, such as lower surface pore sizes for air filtration.

It is expected that the membranes used in this project will have different structures, however they should all be characterized by nodes that are interconnected by fibrils.

### 2.2 MD performance

#### 2.2.1 Performance

El-Bourawi et al (2006) show, in their review, that AGMD’s flux is mostly dependent on the feed side operating conditions. The flux increases as the feed side temperature and/or velocity (to an asymptotic level) is raised. The effect of the feed water concentration is not clear as different authors have had conflicting results. The general consensus on the cold side is that the water velocity only slightly affects the flux, while a rise of the temperature could decrease it. An important factor in MD is the difference between the hot and cold water temperature. When the latter increases, the flux also increases. Regarding the morphology of the membrane, it is generally agreed that the most important factors for AGMD performance are the average pore size of the film and its porosity, which increase the transmembrane flux as they increase.
2.2.2 Membrane requirements

According to Li et al. (2008), only a few authors have looked into the designing and manufacturing of membranes for MD processes. MD membranes need to meet several requirements to be efficient. They must have:

- A good long-term thermal stability to temperatures as high as 100°C.
- An excellent chemical resistance to a variety of feed solutions.
- A high Liquid Entry Pressure\(^1\) (LEP) by using a membrane material with a large water contact angle (high hydrophobicity) and a small maximum pore size at its surface.
- A high permeability by increasing the membrane pore size and porosity and decreasing the membrane thickness and pore tortuosity.
- A narrow pore size distribution in order to prevent the wetting of fraction of the larger pores.
- A Low thermal conductivity by using thicker membranes with high porosity (most hydrophobic polymers have quite similar low thermal conductivity coefficients).

Some of the membrane requirements are contradictory. A small surface pore size, which in turn indicates a small mean pore size, promotes a high LEP while leading to low membrane permeability. Furthermore, thicker membranes decrease the heat loss, while reducing the permeability. It is therefore necessary to find an optimal compromise that impairs neither the permeability nor the heat loss. The optimized combination of those requirements should yield a high mass transport with a very low heat transport.

An additional factor to consider is the tortuosity factor in “tortuous pore” membranes. It is the measure of the deviation of the pore structure from straight cylindrical pores normal to the surface and it is inversely proportional to the membrane permeability. Therefore, the factor must be small, and is often assumed to be of a value of 2 (El-Bourawi et al, 2006).

As reinforcement, a membrane used in MD can have a support. The support must be selected based on its low heat and mass transfer resistances as well as its capacity to prevent deflection or rupture of the membrane.

2.3 Characterization of membranes

MF membranes have morphological structures that are designed to fulfill the application’s requirements as the microscopic structure created by the manufacturing processes strongly affects the performance of the membrane. There are numerous controlled and standard characterization techniques for microporous membranes, which are either aimed at obtaining permeation or morphological properties.

Authors have used different methods to determine the average pore size of membrane pores, such as the use of a Coulter porometer (Martínez et al, 2003) or of microscopic images (Phattaranawik et al., 2003). Furthermore, Woods et al (2010) have compared the measured geometric mean pore size from various methods (AFM, liquid displacement, Hg intrusion, SEM, gas permeation) of commonly used membranes, from Millipore (PVDF) and Pall-Gelman (PTFE), and the mean pore size specified by the manufacturer. These studies have shown that the measured pore sizes are likely to slightly differ from the manufacturer’s values. It is very often unknown which technique is used by a manufacturer to characterize its membranes, and which mean pore size is provided (arithmetic or geometric). It is therefore important to double check the membrane specifications before comparing them.

---

\(^1\) LPE is the pressure at which the liquid begins to leak through the barrier.
2.3.1 Pore size determination

A frequently used method for quantitatively determining the largest pore size of a membrane is the bubble point method which consists in applying a gas pressure to one side of a wetted membrane (typically by isopropanol) and then waiting for the first steady stream of bubbles. The pressure at this point is called the bubble point, and the inverse pressure–pore size relationship for a cylindrical pore is described by

\[ D = \frac{4 \gamma \cos \theta}{\Delta P} \]

Where,
- \( D \) is the pore diameter
- \( \gamma \) is the surface tension of the wetting fluid (21.7 dynes/cm at 20°C for Isopropanol)
- \( \theta \) is the contact angle of the wetting fluid on the surface
- \( \Delta P \) is the pressure difference between gas and liquid.

Pore size determination tools typically assume cylindrical pore sizes as it is hard to know the tortuosity of a membrane. Even though the measurements are not exact, they can provide a general trend of the pore size distribution of a membrane. There are many other variants of this bubble point method, however they will not be discussed here.

Since the bubble point equation only provides the real diameter when the pores are cylindrical, its values will only be used as a comparative tool.

2.3.2 Air permeability

The Gurley number represents the time required for 100cm³ of air to pass through a square inch orifice of a given material at a pressure differential of 4.88 inches of water. In other words, the lower the value, the more permeable is the membrane. This tool is useful to compare the air permeability of different membranes, which could give an insight onto their performance in MD.

2.3.3 Image analysis

Electron microscopy is one of the most common imaging methods used to provide detailed structural information of the membranes. The different types of electron microscopy are Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), Scanning Transmission Electron Microscopy (STEM), and Field Emission Scanning Electron Microscopy (FESEM). The use of either of these tools depends on the quality requirements, costs and availability.

One of the major advantages of TEM over SEM is that the former can distinguish between structures at different heights, which is due to the fact that the contrast between polymer and pore is obvious and the information depth is clearly defined by the thickness of the section (Ziel et al, 2008).

As opposed to SEM, FESEM generates high resolution imaging at low accelerating voltages, which means more accurate representations of the surface morphology.

Electron microscopy images allows the user to clearly differentiate between the pores and the membrane matrix. The images can therefore show the different pore sizes and shapes of the membrane. With the help of an image analysis software, the pore area can be determined as well as the pore sizes and their distribution. The latter is generally fitted to lognormal or normal distributions given by frequencies. Many authors have used this method to characterize the morphology of the membranes (Phattaranawik et al., 2003; Ziel et al, 2008; Nakao S.I., 1994; Hernández et al, 2998).
Typically, SEM requires a coating of the sample when used with standard machines, however, new bench-scale units do not require any type of coating which gives SEM an advantage over Atomic Force Microscopy (AFM). The latter is another type of imaging which allows the study of the surface morphology of the membrane. Through the use of a sharp tip at the end of a microscopic cantilever, it provides three dimensional topographical images of the surface (Khayet et al, 2004). A downside of using AFM with microporous membranes is that it does not differentiate between dead-end pores and normal pores, as it only measures the topography of the surface, whereas SEM may show many of those dead-ends. AFM can however describe the roughness of the surface.

High resolution microscopic images at appropriate magnifications can therefore help estimate, for comparison purposes, the morphologies of the surfaces of films (porosity, pore size and pore size distribution). In this thesis, only SEM images are used.

2.3.4 Porosity measurement

Another way of measuring the porosity of the membrane is by measuring the mass of the membrane with and without its backing (Zhang et al, 2010). By using an accurate scale combined with precise measurements of the sample’s area and thickness, this method can provide reliable porosity measurements. This step is used to find reference values for the determination of the pore sizes in the image analysis process.

2.4 Effect of membrane characteristics

2.4.1 Film

El-Bourawi et al (2006) show, in their review, that AGMD’s performance is mainly affected by the film’s pore size and porosity, which improve the flux as they increase. The membrane thickness only slightly affects the flux, which could be positive or negative. However, an increase in membrane thickness can reduce the heat conduction through the membrane, which is an order of magnitude higher than the sensible heat transferred by vapor flow in the membrane.

Since the MD flux is inversely proportional to the membrane thickness times its tortuosity (El-Bourawi et al, 2006), the latter plays an important role in the flux. Therefore, if the bulk of the membrane is highly tortuous, a lower flux can be expected.

Woods et al (2011) tested the importance of a membrane’s pore size distribution based on the dusty gas model. The results were then compared with experimental data from the literature. They found that AGMD was the least affected with the error being less than 7 % for all the considered cases (and less than 1% for some cases). Those values are based on geometric standard deviations to consider wide and narrow distributions. It is obvious that for narrower distributions the errors are very small. Thus, it could be assumed that the distribution has only minor effects on the flux as long as the distribution is not too wide.

During AGMD applications, a membrane is subjected to pressure created by the feed water and becomes compacted, thus reducing its thickness. A smaller thickness implies a higher thermal conductivity coupled with lower porosities and pore sizes, indicating a decrease in flux. This result was also found by Zhang et al (2011) in DCMD where the flux decreased as the pressure rose. However, membrane compaction can positively affect the performance of a membrane as well, according to Lawson et al (1995). To a certain degree of compaction, the membrane permeability can be enhanced (by up to 11% in their work). The effect of the compaction on the mass transfer by reducing the diffusional path length through the film can outweigh the effect of the change in pore sizes and porosity. A conservative model developed by Lawson...
et al (1995) show (Fig. 5) shows that the compaction of a membrane ($\delta/\delta_0$) with an initial porosity of 80% would have an increase in permeability ($[N/\Delta P]/[N/\Delta P_0]$) until a compression of about 40% of its initial thickness is achieved.

![Fig. 5. Effect of compaction on permeability of membranes with various initial porosities, $\epsilon_0$. Calculations assume the permeability to be proportional to the porosity squared divided by the membrane thickness. (Lawson et al 1995)](image)

It has been suggested (El-Bourawi et al, 2006) that roughness of a membrane may influence the polarization effect in MD, as well as the permeate flux. Khayet et al (2004) found that the pure water flux increased with larger the roughness parameters in a VMD setup, and they suggested that it could mainly be linked to the increase in porosity and pore sizes.

### 2.4.2 Membrane backing

Zhang et al (2010) found that a membrane with a backing layer with more open structure increased the performance of the membrane in DCMD. They suggested that a thin scrim, as a backing layer, with wider accessible spaces to the surface of the film should provide an increase in flux, and that its geometric structure may be more important than its porosity (for membranes with pore sizes between 0.2 and 1µm). Furthermore, it was found that the hydrophobicity of the membrane was not as important as other physical features.
3 Objective and method of attack

MD is a very promising new technology that could be applied in many different sectors, and coupled with renewable energies and/or waste heat to produce pure water at a low-cost. MD is extremely dependent upon the performance of the membrane, as it dictates the mass transfer, the heat transfer and the long-term application. Unfortunately, there are no commercially produced MD-specific membranes at this point in time. It is therefore imperative to create and develop new membranes that are highly permeable and efficient with a very excellent long term capabilities.

This project aims at finding correlations between membrane characteristics and their performance, in order to define the optimal morphologies and operating conditions for a MD-specific membrane. To do so, the characteristics 3 PTFE membranes initially designed for MF will be determined through porosity measurements and microscopic images, while their performances will be measured by measuring the air permeability and by testing them on an AGMD bench-scale unit.
4 Methodology

4.1 Material

The initial bench-scale unit and the membranes used in the experiments were provided by Xzero AB, while the new components of the upgrade to the set up were provided by the Department of Energy Technology of KTH. The SEM images were provided courtesy of Bruker AXS Nordic AB. As mentioned previously, all three membranes are made of a PTFE film with a PP backing. The membranes are manufactured by three different companies of which only two are known, namely Gore and Donaldson. The manufacturer of the third membrane did not wish to be identified for proprietary reasons, and is therefore referred to as “Membrane C” in this work.

4.1.1 Initial data

The initial data provided by the manufacturers are shown in Table 1. The available data for Membrane C are only for the unsupported film, while the characteristics of the supported Gore membrane are known, as well as the thickness of its unsupported film.

Donaldson, however, provided us with conflicting characteristics for the supported and unsupported membrane. The data of the former was mainly given in ranges, while the latter was given with average values. According to the manufacturer, the unsupported film has a Gurley value of 10.46 seconds, while the supported film has a Gurley value between 23 and 30 seconds. Those values seem unrealistic.

The bubble point pressure for Donaldson and Gore are very close, it can therefore be assumed that they have a somewhat similar largest pore size.

<table>
<thead>
<tr>
<th>Membrane</th>
<th>Donaldson</th>
<th>Gore</th>
<th>Membrane C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>ePTFE</td>
<td>ePTFE</td>
<td>ePTFE</td>
</tr>
<tr>
<td>Support</td>
<td>Typar (PP)</td>
<td>none</td>
<td>PP</td>
</tr>
<tr>
<td>Pore (µm)</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Thickness (µm)</td>
<td>203.2 to 254</td>
<td>74</td>
<td>280 / 65a</td>
</tr>
<tr>
<td>Gurley (sec)</td>
<td>23 to 30</td>
<td>10.46</td>
<td>17.80</td>
</tr>
<tr>
<td>Bubble point (bar)</td>
<td>1.52 to 1.72</td>
<td>1.62</td>
<td>1.57</td>
</tr>
</tbody>
</table>

Table 1. Initial membrane data

Notes:
a) film thickness for gore

4.2 Morphology characterization

4.2.1 Porosity

This step consists in measuring the porosities and thicknesses of the films and backing layers. They are found by determining the masses of the full membranes (film and backing layer combined) and the backing layers on a high precision scale and comparing the measurements with hypothetical membranes without pores. To do so, the sample dimensions (areas and thicknesses) must be known to determine the exact volumes of the samples.
Once the samples are weighed and the dimensions measured with a micrometer, the porosities can be calculated as follows:

$$
\varepsilon = 1 - \frac{V_{full}}{V_{nop}}
$$

With,

$$
V_{full} = V_{film} + V_{back} = \frac{m_{film}}{\rho_{PTFE}} + \frac{m_{back}}{\rho_{PP}}
$$

$$
V_{nop} = V_{fnp} + V_{bnp} = A_{film} t_{film} + A_{b} t_{back}
$$

Where,

- $t$ is the thickness [mm]
- $V$ is the volume [mm$^3$]
- $A$ is the area [mm$^2$]
- $m$ is the mass [g]
- $\rho$ is the density [g/mm$^3$]

PTFE and PP, respectively, have a density between 2.1 and 2.3 g/cm$^3$ and 0.90-0.92 g/cm$^3$ (Kipp, 2004). Since the densities of those polymers are usually found in ranges, the average value is chosen.

### 4.2.2 SEM images

The SEM images were taken by a Hitachi Tabletop Microscope TM3000 provided by Bruker AXS Nordic AB. Images for each membrane sample were taken at different magnifications (between x60 and x10 000) for the film and the backing.

Most film images were taken with the TM3000 set to an accelerating voltage of 5kV for a better surface description, while some were taken at 15kV to emphasize the subsurface layers. With regard to the backing, most images were taken with the 15kV set up as the fibers were thick enough to provide high resolution imaging.

Images of each membrane are taken at similar magnifications of regions that show the general pattern of the membrane. Those images are then analyzed to compare the membrane’s surface porosities and morphologies.

### 4.3 Performance characterization

#### 4.3.1 Gurley tests

In order to have a more accurate idea of the performance of the membranes, samples of each membrane were tested (front and back) using the standard ISO 5636-5:2003 to obtain the Gurley values.
4.3.2 AGMD bench-scale

4.3.2.1 Improvements

The AGMD bench-scale setup initially provided by Xzero AB did not have any control and measurement devices. On the hot side, the setup only provided one feedwater flowrate, and the temperature could only be measured by hand in the tank. On the cold side, the fluctuating flowrate was very hard to control while the temperature could only be measured by hand at the level of the drain.

This project required a full control and monitoring of the temperatures and flow rates, therefore some modifications had to be done.

4.3.2.2 Set up

The new set up is shown in Fig. 6. Two heaters were installed on the 24 liter tank, with a combined power of 4.5 kW. However, these heaters are not very stable, which creates slight fluctuations of about ± 3°C of the temperature in the tank during a run. The cold water inlet temperature is not under our control.

Rotameters with built-in control valves were installed on both sides of the setup. Since the pump on the feed side is not adjustable, a bypass was added with a needle valve to control the flow rate going into the module.

Fig. 6. AGMD bench-scale unit setup

To measure and monitor the feed and cold water temperatures, thermocouples were installed at the inlets and outlets of the AGMD which were connected to a data logger (Keithley 2701 DMM with a 7706 card).
4.3.2.3 AGMD module

The AGMD module consists of a 2.4 cm gap between two condensation plates, behind which are located the cooling channels in a serpentine shape. The cassette fitted into the module has 2 membranes glued onto it, each with an area of 0.1 m², with the film placed towards the inside, and the backing material towards the condensation plates. The flow comes in from the bottom of the cassette, and flows out from the top, as seen in Fig. 7. This gives an air gap of about 9 mm on each side. However, when the cassette is filled with water, the membranes bulge out onto the condensation plates. Despite the negative effects this has on the flow in the cassette, it will be assumed that the flow against the membrane is the same everywhere. Furthermore, it is assumed that the hydrodynamic conditions are identical for each membrane.

![Membrane Cassette](image)

Fig. 7. Membrane Cassette

4.3.2.4 Experiments

The AGMD experiments consist in analyzing the performance of the membranes under different operating conditions, such as different flow rates and temperatures.

The operating conditions on the cold side are kept constant at a feed flow rate of 1.5 LPM and an average inlet temperature of about 8°C. This temperature might vary slightly as it is not under our control.

On the hot side, with tap water as feed water, the operating conditions that are modified are the following:

- The feed water temperatures: 45°C, 60°C and 75°C
- The feed water flow rate (average flow channel velocity): 3 LPM (0.022 m/s) and 5 LPM (0.037 m/s)

This generates a total of 6 runs per membrane, during which the temperature variation between the inlets and outlets of the module are measured, as well as the pure water flow rate and conductivities. When the operating conditions are changed, measurements are not taken until the system reaches stability.

As it is very hard to estimate the temperatures on the interfaces of the membranes and the flow conditions at the different operating conditions, it is assumed that the membranes are tested under the same hydrodynamic and thermal conditions, and thus the same boundary layer conditions.

The performances of the membranes are compared by analyzing the pure water flow rates and the energy requirements per m³ of water produced (in kW.h/m³). The latter is found by determining the heat transfer between the inlets and outlets ($\dot{m}c_p\Delta T$), which is then divided by the pure water flow rate.
5 Results and discussion

5.1 Morphology

5.1.1 Porosity by mass

The measurements of the porosities and the thicknesses are shown in Table 2. As the membranes are porous and compressible, it was hard to get accurate results for the thicknesses due to the force of the micrometer acting on the surface. To compensate for this issue, up to 30 measurements were taken per sample and then averaged to obtain a representative value. Therefore, those values are only approximations, and could generate a source of error of ±10µm. Another source of error could be the density values which were taken as an average of the ranges found in the literature.

When removing the backing from the film, it was noticed that Membrane C had the strongest bonds between those 2 layers, followed by Donaldson, and finally Gore. This suggests a difference in the manufacturing process. A backing layer is typically bonded to the film by being exposed to high pressure and heat, which means that the thickness of the film can slightly be reduced or modified during the process. A stronger bond could mean that the sample was subjected to the pressures and temperatures either to a higher degree or to a longer period of time. Moreover, some of the film could, to a certain extent, be pushed into the pores of the backing layer, thus providing inaccurate measurements for the thicknesses.

<table>
<thead>
<tr>
<th>Membranes</th>
<th>Gore</th>
<th>Donaldson</th>
<th>Membrane C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Full</td>
<td>Back</td>
<td>Film</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reference</td>
<td>280</td>
<td>65</td>
<td>237.1</td>
</tr>
<tr>
<td>Measured</td>
<td>278.3</td>
<td>223.2</td>
<td>220.4</td>
</tr>
<tr>
<td>For porosity</td>
<td>280</td>
<td>215.0</td>
<td>237.1</td>
</tr>
<tr>
<td>Mass (mg)</td>
<td>314.2</td>
<td>194.8</td>
<td>270.7</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>73.4</td>
<td>72.6</td>
<td>68.5</td>
</tr>
</tbody>
</table>

Notes:
- a) Average of the range provided by manufacturer
- b) Thickness calculated from the other values
- c) This value is an approximation given by the manufacturer.

The thickness measurements done on the Gore membrane were the closest to the reference values provided by the manufacturer. The full membrane values were almost identical, while the film measurement was 15% lower. For this membrane, it is assumed that the reference values are correct, and are therefore used to calculate the porosity.

Gore’s set of measurements suggest that the method used for the measurements provide acceptable results within a range of ±15%, which is in accordance with the error margin prediction.

The measured thickness of Donaldson’s full membrane is very close to the average of the reference value while the backing layer slightly differs, therefore, it could be assumed that those values are within the real ranges. The measured thickness of the film is, however, 77% smaller than the reference value. This difference in size cannot be solely due to the previously mentioned manufacturing processes. By using the measured and reference values and by setting the total thickness as being correct, the film would,
respectively, have a porosity of 53% and 89%. Furthermore, according to the manufacturer, the porosity should be over 85%. The two sets of data suggest that we’re dealing with two different membranes.

As Membrane C has a stiff backing layer, which helps to reduce the errors in the measurements, its measured thickness is assumed to be correct. The thickness of the film is 58% lower than the reference value, which, when considered with the strong bonding with its backing, could be due to the high pressure and heat from the manufacturing process. This would mean that the film had a thickness of 80µm before its bonding to the backing. As we do not have any other information available at this point, a measured thickness could be assumed to be correct, thus giving the film a porosity of 65%.

If it is assumed that the measured values are all correct, Gore would be the membrane with the highest film and total porosities. Donaldson would have the second highest total porosity as well as lowest film porosity, while Membrane C would have the lowest backing layer porosity. However, Gore and Donaldson have somewhat close total and backing porosities.

Furthermore, if it is also assumed that, initially, all three membranes had the higher porosities and that the model in Fig. 5 is somewhat accurate, the compaction that Donaldson and Membrane C endured could increase their resistance to the flux, while Gore’s compaction could be slightly beneficial.

5.1.2 SEM images

The SEM images of the film and backing layer are discussed in this section. Because of the somewhat obvious differences between the different membranes, the analysis of the images using an image analysis software was not required, mainly due to it inaccuracies from the low resolution images.

Under each SEM image, the membrane name and the scale of the image can be found. The membrane marked NA represents the images of membrane C. The letters F and N located under the scale bar indicate the accelerating voltage of the image, respectively 5 and 15kV.

5.1.2.1 Overview

An overview of the membranes at a low magnification (Fig. 8) clearly shows the structure of the surface of the membranes. Gore and Donaldson have somewhat similar morphologies, consisting of a small surface pores, while Membrane C has larger pores.

Compared to Gore, Donaldson’s surface has a lower porosity as well as smaller pores that are more dimensionally stable and evenly spread. Looking at the structures of the membranes shown in the magnifications of Fig. 8, it can be seen that the surface of Gore and Donaldson are mainly composed by nodes. Their fibrils seem to be mostly located under them, as opposed to Membrane C where they are prominent on the surface. Moreover, Donaldson’s nodes are larger and denser than the others. This could be due to a heat treatment of the surface, which typically reduces the pore sizes and the porosity, thus increasing the surface of the matrix.
In addition to the issues with the data regarding the thickness of the film, the latter is also affected by the backing material. The image of the film in Fig. 9 clearly shows that some of the fibers of the backing are reducing the porosity of many parts of the section seen. All those local areas with lower porosities from the compaction of the film create a resistance to the flow, thus increasing the total resistance to the flow through the membrane.
The backing layer, also shown in Fig. 9, shows that many fibers are fused together, increasing the overall thickness of the average fiber. Thicker fibers could, on one hand, increase the average size of the open areas by clustering fibers together which could provide a higher flux (Zhang et al, 2011), and on the other, increase the total resistance to the flux by blocking passageways. This depends on the overall arrangement of the fibers, which is hard to estimate based on the provided data.

The compaction of the film by the fibers of the backing and the fusion of those fibers coupled with the probable heat treatment of the surface of the film suggests a lamination at high pressure and temperature for a relatively long time. This type of lamination could be done using the same patented method from Donaldson mentioned earlier.

Moreover, this type of pressure and heat applied to a film could very well fuse some of the fibrils and nodes together in the first layers. This is suggested by the SEM images at 5kv and 15kv of the film (Fig. 10). Those two images show the morphology of the membrane on the surface as well as under it. It can be seen that the first layers of the film are very dense, and that a typical structure of nodes and fibrils is hard to find. This suggests a compression of the membrane with a fusion of the material on the first layers of the film, which implies a lower thickness and a potentially higher resistance to flux.

The characteristics of the Donaldson membrane seen in the SEM images seem to indicate that the film is compressed. This would mean that the 74µm thickness mentioned by the manufacturer probably represents that of the film prior to any treatment or lamination. The membrane was probably heat treated for a special application in microfiltration.
As mentioned previously, the surface of the gore membrane is more porous with larger pores than Donaldson’s. As it can be seen in the 5kV and 15kV image in Fig. 11, the surface of the film has less open spaces than the first layers below it. This could suggest a heat treatment of the surface, but to a much lesser extent than Donaldson.

Also, the fibers of the backing material only exhibit slight fusion between some of them. This could have occurred during the lamination process, which would mean that it was down at lower pressures and temperatures, or for less time.

The characteristics of a typical PTFE structure with nodes and fibrils can be seen clearly. Moreover, the bulk of the membrane seems to have many pores larger than 0.2µm. However, this image only represents the first layers of the film and therefore cannot be used to determine its average pore sizes.

The backing layer is composed of fibers with an average diameter about twice the size of Donaldson’s (Fig. 12). For backing layers of about the same thicknesses and masses (Table 2), the one with the larger fibers will provide more open areas for the film, which should result in higher fluxes (according to Zhang et al [2011], as mentioned previously).

The roughness of the surface seems to be less than Donaldson’s, as it is more porous with larger and uneven pores. It is still unclear whether this difference in roughness has a notable impact on the permeate flux.

Fig. 10. Donaldson film at accelerating voltages at x10k: 5kV (left) and 15kV (right)
Fig. 11. Gore film at x10k with accelerating voltages of 5kV (top left) and 15kV (top right), and its backing at x100 (bottom left)

Fig. 12. The backing material fibers of Gore (left) and Donaldson (right)
5.1.2.4 Membrane C

The surface of the film of membrane C (Fig. 13) consists of many nodes and fibrils forming large surface pores.

![Image of Membrane C film at 5kV and x5k (top left), 15kV at x5k (top right) and x10k (bottom)]

**Fig. 13.** Membrane C film at 5kV and x5k (top left), 15kV at x5k (top right) and x10k (bottom)

The membrane seems to be composed of a multitude of layers of a structure composed of large pores and small nodes. This could be advantageous for the vapor transfer as it would pass mostly through slightly tortuous “bottle-neck” types of passages, which can reduce the resistance to the flow. Moreover, this type of structure could reduce the amount of “dead-end” pores. Based on the SEM images available, Gore and Donaldson do not seem to possess this type of structure, but one with larger nodes and more tortuous paths that could hinder the flow.

The main issue with Membrane C is its backing layer. The latter, shown in Fig. 14 has a very dense structure with very low porosity. The layer has a scrim-like design achieved by fusing the fibers together. This fusion creates a strong resistance to the flow, while the section in between them is does not seem porous enough to compensate for it. Those sections do not show any open areas for the film. It is unknown whether the fusion of the backing fibers has occurred before or during the lamination process, but the latter case could explain the strong bond observed when the layers were separated, as well as the smaller film thickness when measured.
5.1.3 Gurley tests

As mentioned previously, the Gurley values represent the time required for 100cc of air to pass through the membranes. Each sample was tested with the flow passing through the back and the front, and the results are shown in Table 3.

**Table 3. Gurley Values**

<table>
<thead>
<tr>
<th>Tested through</th>
<th>Donaldson</th>
<th>Gore</th>
<th>Membrane C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back side</td>
<td>26.10</td>
<td>11.20</td>
<td>11.80</td>
</tr>
<tr>
<td>Film side</td>
<td>24.58</td>
<td>10.51</td>
<td>11.15</td>
</tr>
<tr>
<td>Reference</td>
<td>Film + backing</td>
<td>23 to 30</td>
<td>17.80</td>
</tr>
<tr>
<td></td>
<td>Film only</td>
<td>10.46</td>
<td>-</td>
</tr>
</tbody>
</table>

The results of the measurements through the film side show that Gore has the lowest Gurley value, and is closely followed by Membrane C. Donaldson, however, has a value that is about 2.5 times larger than Gore’s as well as its own film. This measurement fits in the range provided by the manufacturer for the full membrane. Gore’s measurement is about 40% lower than the reference value.

Even though the morphologies of Gore and Membrane C are very different, their air permeability is very close. As Membrane C’s backing layer is very dense, its film must be more permeable than Gore’s to compensate. Yet, Gore’s film is more porous than Membrane C, therefore the latter is probably less tortuous, which increases the permeability.
Based on this data, one would expect Gore and Membrane C to perform somewhat similarly, and Donaldson to be far behind.

All three membranes are more permeable from the back side then the film. Moreover, Donaldson exhibits the largest difference (over two times) between the Gurley values for the back and the film. This is probably mainly due to the low porosity and pore sizes on the surface which increases the head losses.

5.1.3.1 Additional tests needed

To produce a better comparison of the membranes, additional tests should be performed. SEM images of the cross section of each membrane would be beneficial as it would allow the confirmation of the compression hypothesis. A permeation test to determine the pore size distribution of Gore and Membrane C would also be useful to determine a link with the performance. Furthermore, testing the contact angles and surface chemistry may also yield results.

5.2 AGMD testing

5.2.1 Issues during the experiments

It was observed, during every run, that the heater did not provide a constant temperature. The heater functions in an oscillating manner, by increasing then decreasing its power. Consequently, the temperature of the feed water flowing into the cassette was fluctuating. By manual regulation of the power, it was possible to limit the fluctuation to ±3°C of the aimed temperature. This decreases the accuracy of the tests, however, since this issue occurred for every run, it can be assumed that every membrane was subjected, on average, to the same temperatures. The results are therefore comparable.

Furthermore, the temperature of the water on the cool side, which is not controllable, is at 18°C at the beginning of each run and then decreased continuously until it stabilized around 8°C at a certain point in time. As time was limited, some tested began at temperatures over 8°C.

Also, the flow rate on the cool side was stabilized at 1.5LPM, which represented the lowest limit of the flow meter. This type of condition is not optimal, and could create issues with the accuracy of the flow rate in the cooling channels. This is probably why the temperature measured at the inlet and outlet of the cool side of the cassette gave unrealistic values for the heat absorbed by the water. Those values are therefore discarded for this project.

5.2.2 Pure water conductivity

The pure water conductivity was similar for all three membranes. The values fluctuated on average between 1.1 and 1.5 µS/cm, which are very satisfactory results.

5.2.3 Pure water production

The pure water flow rates produced at different temperatures and feed water flow rates are shown in Fig. 15. The average of the 3 measurements taken per run was taken as a representative value because the differences between them were very small (generally 0.2 ml/min). A margin of error is therefore not considered in this case.
Fig. 15 clearly shows that Gore always produces the highest pure water flow rates. It is also clear that the flux increases with an increase in temperature and/or feed water flow rate.

At 45°C, the performance of Membrane C is very close to Gore's, but as the temperature increases, the flux from the latter rises at a higher rate than the former, especially at 5LPM. This means that Gore is more responsive to the feed water’s temperature and flow rate.

Donaldson has a significantly lower pure water flow rate than the other membranes, except at 75°C and 5LPM where it reaches the level of Membrane C. The latter’s increase in flux with rising temperatures at this feed water flow rate is somewhat linear, whereas the other two increase much faster as of 60°C. However, at 3LPM, all 3 follow the same type of evolution. This suggests that Membrane C does not favor as much as Gore and Donaldson the combination of high velocities with high vapor pressures.

Even though Gore and Membrane C have very similar resistances to air flow, they seem to act differently with vapor, particularly at high vapor pressure. One possible reason could lie within the surface layer of the film. Because of the large surface pores, surface wetting could occur, which would reduce the flux due to the lower temperature of the water within the pores. If this is the case, it would mean that the surface morphology may play an important role in MD, and should be optimized. Another possible explanation could be that the increasing pressure causes some vapor to be trapped in the film due to the flow resistance caused by the backing layer.

Gore and Donaldson seem to have the same type of responsiveness to a change in temperature or flow rate. However, Gore’s results are much higher than Donaldson’s, which can be mainly explained by the higher porosity and the less air flow resistance. In this case, the Gurley numbers do predict the performances, which is not the case for the Gore and Membrane C.

Despite the large difference in air flow resistance between Membrane C and Donaldson, similar fluxes are obtained at 5LPM and 75°C. This shows that large differences of Gurley values do not necessarily imply better performances at every operating condition. Nevertheless, air permeability tests still provide an insight into the overall trend of the performance of a membrane, and is therefore useful as a comparative tool.
Also, the fact that Gore was the only membrane that did not exhibit any clear signs of the lamination process could imply that the manufacturing processes have more effect on the flux than previously anticipated.

### 5.2.4 Energy consumption

The energy requirements for the production of 1 m³ of pure are shown in *Fig. 16*. The general trend is a decrease of kWh required as the temperature and/or flow rate of the feed water increase. Gore requires the least energy for the production at every condition of operation, while Donaldson requires the most, except at 75°C, where it is in the same area as Membrane C.

![Fig. 16. Energy requirements per m³ of pure water produced (hot side)](image)

As mentioned previously, to calculate the energy requirements per m³ of water produced, the temperatures at the inlet and outlet of the cassette must be known. However, due to the issues with the heater, the temperatures fluctuate of about ±3°C, which creates uncertainties about the measured values. For example, instead of having a stable temperature of 60°C, the inflow actually varies between 58 and 62°C. Furthermore, because of the temperature change, a real steady state cannot be reached, therefore the values measured are subjected to a certain delay. If the temperature at the inlet starts to increase at a “$T_i$”, the outlet is still discharging the feed water that was delivered earlier “$T_{i-n}$”. Therefore the $\Delta T$ measured is not the one that one would measure at a steady state. By considering an error margin of ±1°C for $\Delta T$, it is possible to see the range in which the real value is probably located. The error margins displayed in *Fig. 17* show that the uncertainty is quite large for the lower temperatures, and wider for higher flow rates.

At 3LPM, the upper limits of Gore’s error margin at 45 and 65°C overlap with the lower limits of Membrane C, while the latter’s upper limit only barely overlaps with the lower limit of Donaldson at 65°C. It is therefore possible that Membrane C may be slightly more efficient than Gore at the first two temperatures, however, based on the values of Gore at 75°C, it could be assumed that this is not the case. Donaldson’s values could easily be considered to always be higher than the other membranes.
At 5LPM, the large overlapping of the error margins of Membrane C with Gore at 45°C, as well as with Donaldson at 75°C, make it very hard to determine the most efficient membranes. Nevertheless, the tendency of Gore’s curve does suggest that it is overall the most efficient of the 3 membranes.

Fig. 17. Error margins for the energy requirements per m³ of water produced
6 Conclusions

The following conclusions can be drawn from this study:

- Based on the results from the comparison of 3 different PTFE membranes with a non-woven PP backing, the characteristics that seem to promote a higher flux are:
  - A backing layer that doesn’t restrict the vapor flow in a significant way, and that possesses large open areas,
  - A film with high porosity and low tortuosity,
  - A film small thickness with a resistance to compaction,
  - Surface pore sizes small enough to avoid surface wetting,
  - A film that has not been subjected to thickness altering procedures.

- The membrane characteristics provided by manufacturers seem to differ, very often, from the measurements. This has also been mentioned in many references. In the Donaldson case, the manufacturer first sent us the values for the film, not the full membrane. Moreover, the data for the film corresponded to those of a film that had not been laminated onto a backing layer or heat treated, and not to the membrane used in this project, which differed significantly. With regard to Gore, the Gurley value was much higher than the measured one. If a comparison was done solely based on the data provided by manufacturers, the results would have been erroneous.

- The performance of the membranes in MD cannot be fully predicted by the morphologies or the air permeability. The latter was clearly shown by the closeness of the measured Gurley numbers between Gore and Membrane C, as well as the closeness of the fluxes at high temperature and flow rate between Membrane C and Donaldson. However, when the Gurley values are dissimilar, they can be used to provide an overall approximation of the performance of the membranes.

- There seems to be a more important link between the manufacturing processes and the performance than previously anticipated.

- The efficiency of the membranes increases as the feed water temperatures and flow rates rise, which means that ideally one should aim for the highest possible operating conditions. However, this is not realistic. Higher temperatures and flow rates require larger costs. Therefore it is necessary to find a cost effective solution.
7 Future work

7.1 AGMD set up

To increase the accuracy of the measurements, the setup must be mounted with heater that provide a stable output. Moreover, a new system for the cool water is required which allows a better control of the temperature and the flow rates. This system should be designed as a loop in order to avoid any wastage of water. Also, better insulation is needed for the tank to reduce the heat loss to the ambient air.

7.2 Membrane development

The following are some points to consider for the next steps of this work as well as for the development of membranes for AGMD:

- By testing new membranes and adding new tests, a more comprehensive and accurate guideline for the design of MD specific membranes could be create. Then, the findings should be discussed with manufacturers in order to create new MD specific membranes.

- The membranes should also be tested using different feed waters.

- More research should be done regarding the effect of the morphology of the backing layer. As the pressures acting on a membrane in MD are relatively low, new scrims should be developed and tested with very large open areas.

- The surface heat treatments and compaction of the film in the performance of membranes in AGMD should be looked into more closely.

- As the membrane is the keystone of MD, it is imperative to create MD-specific membranes. To do so, more work should be in comparing the different MF designs. In order to do a more thorough and comprehensive comparison between one’s experiments and membranes used by other authors, guidelines and standards for tests to characterize the membranes should be developed to create a similar basis for comparison. In general, authors select different methods and levels of accuracy to describe the morphologies and the performances of the membranes they use. This makes it impossible to accurately compare the membranes used in different studies. However, if every membrane is characterized following the same guidelines, the comparison would be much more effective, which would facilitate the development of MD-specific membranes to maximize the performance and efficiency.
Bibliography


Appendix A

Commission FPP 9

Testing of Paper

Sample:       Donaldson, Membrane C & Gore & X
Arrived:      2011-01-31
Date of testing: 2011-02-07
Tested by:  Samadnouri Shadi

Methods


Results

Reported results refer to received samples
see appendix

Stockholm 2011-02-07
INNVENTIA AB
Material Processes

Marie Bäckström
Manager, Fiber Engineering & Testing
### Results

<table>
<thead>
<tr>
<th></th>
<th>Donaldson</th>
<th>Gore</th>
<th>MembraneC</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air resist. Gurley s</td>
<td>26,1</td>
<td>11,2</td>
<td>11,8</td>
<td>15,3</td>
</tr>
<tr>
<td>CoV%</td>
<td>1,9</td>
<td>24</td>
<td>2,4</td>
<td>13</td>
</tr>
<tr>
<td>Air perm Gurley S1 μm/Pa·s</td>
<td>5,2</td>
<td>12,1</td>
<td>11,4</td>
<td>8,8</td>
</tr>
</tbody>
</table>

S1 = smooth side