Membrane Distillation

Study of Membrane Distillation unit at the Duke Smart Home.

Jack Larsson

ABSTRACT

The basic concept of a Membrane distillation unit is presented, thereafter improvement on the current configuration is presented.

Department of Energy Technology
Royal Institute of Technology
Stockholm, Sweden

Table of Contents

Introduction

Membrane distillation processes are mainly used in industry applications where there is a need for super clean water. Although there are hopes that membrane distillation will be a cheap technology in the future for making drinking water. In USA today bottled water is a big industry and Reverse Osmosis is one of the technologies used to get clean water. Reverse Osmosis although is a very electric consuming process and since electricity is a very pure energy it's quite wasteful to use it for production of drinking water. One of the big advantages with Membrane distillation (MD) is that the process can be run with low graded heat as the main energy source.

For this specific project we are looking at implementing this technology in the smart house on the Duke campus. Currently the house has warm water produced by solar collectors and these will hopefully supply enough heat to be used as the low graded heat source for the membrane distillation unit. There are also big tanks of collected rainwater that could be purified into drinking water. Today the rainwater is used for toilets, washer, and irrigation. One of the goals of the smart home is to go "off grid"; this will most probably be achieved by being a net zero house where most of the electricity would be provided by a sterling solar engine and solar panels. The sterling engine needs cooing and this would be a perfect opportunity to get heat to the Membrane Distillation unit.

However, a first step is to install a small Membrane Distillation unit that runs on the solar heated warm water. This is a relatively new concept and no earlier examples where this has been done can be found.

Goal of the project

To get an understanding of the working principles of a MD unit and find out how the yield can be improved. Find out how the prototype constructed at Duke and suggest improvements on it according to the theory.

Working principle of a Membrane distillation process.

The following chapter will give a short overview to the working principle of a membrane distillation.

Membrane distillation is a process where warm water flows on one side of the membrane and evaporates through the membrane due to a lower partial pressure of water on the other side. The Figure below illustrates the process where the warm dirty water is flowing on the left side and evaporating through the membrane in to the right side where it is condensed. The driving force of the process is the partial pressure difference, which is directly linked to temperature difference between the warm and the cold side.

The membrane in the process is a semipermeable hydrophobic membrane, other places you can find this types of material is GORE-TEX® clothing which is wide spread.
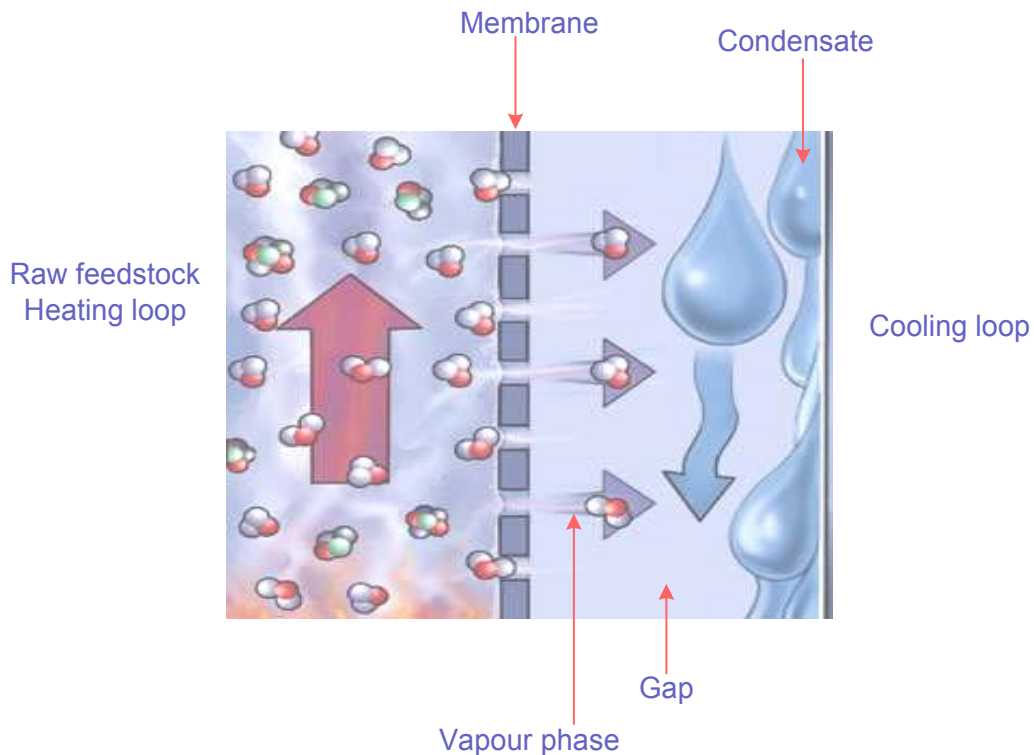
Figure 1: Illustrative picture of the distillation process (Chuanfeng Liu, 2005)

Characteristics

Advantages:

- 100% (theoretical) rejection of ions, macromolecules, colloids, and other non-volatiles.
- Lower operating temperatures than conventional distillation
- Low sensitivity to variations in process (e.g. pH and salts (L. Martinez, 2001))
- Good to excellent mechanical properties and chemical resistance
- Potential lower capital costs compared to RO (Reverse Osmosis)

Disadvantages:

- Higher energy intensity (although a low grade heat might be used)
- Low yield in non-batch mode
- Sensitive to surfactants
- Volatiles cannot be completely separated (such as Ammonia and carbonates)
- Not yet fully commercialized

Different setups

There are 4 different types of Membrane distillation processes(Kevin W. Lawson, 1997):
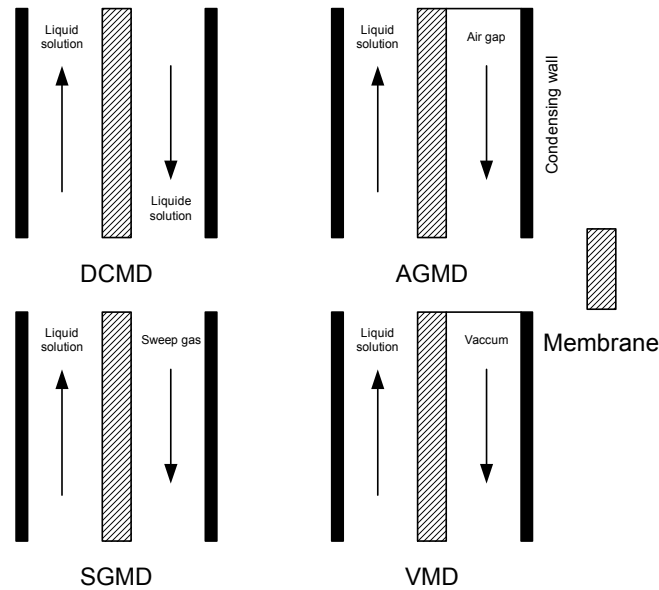
- DCMD (Direct Contact Membrane Distillation)
- AGMD (Air Gap Membrane Distillation)
- SGMD (Sweep Gas Membrane Distillation)
- VMD (Vacuum Membrane Distillation)

The most common ones are DCMD and AGMD; the latter one is preferable. The DCMD has relative low heat utilization due to conduction through the membrane. It also needs clean cold water on the cooling side. This is unsuitable when the goal is to get clean water. A problem with the AGMD is that it has a relative low yield.

Mathematical description

A prototype of AGMD-type has been tested on Duke campus and is therefore the one of the biggest interest for this study. A mathematical model is presented here, both for the yield and the energy consumption of an AGMD-unit.

Mathematically the flux and the energy flow can be described by equations below, if seen as one-dimensional and steady state (A.-S Jönsson, 1985). According to the Duke students a steady state is reached after approximately 15 [min], (Eric Esch, 2010).

$$Q = 4.1 * 10^{-3} * \frac{1}{b / (\phi * \sqrt{T_h}) + L / \sqrt{T_c}} * \ln\left(\frac{1 - V_c}{1 - V_h}\right) \qquad (1)$$

$$E = \frac{1.5 * 10^{-3} * (T_h - T_c)}{\left(b / \gamma\phi\sqrt{T_h}\right) + L / \sqrt{T_c}} + 1.4 * \ln\left(\frac{1 - V_c}{1 - V_h}\right) * \frac{b / \left(\gamma\phi\sqrt{T_h}\right)}{\left(b / \phi\sqrt{T_h}\right) + \left(L / \sqrt{T_c}\right)} \qquad (2)$$

Where:
Q is the flux
E is the energy flow
L is the distance between the membrane and the cooling plate
ϕ is the porosity of the membrane
T_h and T_c is the bulk temperature on hot resp. cold side
b is the thickness of the membrane
V_h and V_c is the mole fraction of water vapor on the hot resp. cold side
And γ is a function dependent on the thermal conductivity of the membrane and the porosity and the overall thermal conductivity that is varying with the flow.

If this is analyzed further we can see that to gain a big flux the distance L and the thickness b should be minimized. What is optimal is hard to say but many systems today use L of approx 2 [mm] and thickness of 0.2 [µm] (Chuanfeng Liu, 2005). In figure below there is an illustration how the flux varies with different values for L and b.
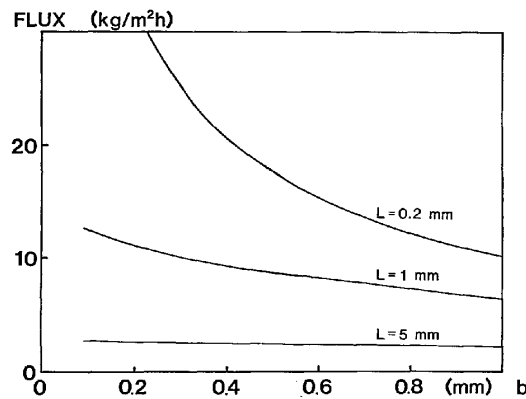

Figure 2: Flux variation of b and L (A.-S Jönsson, 1985)

We also know that the higher the temperature the higher the mole fraction gets. Therefore, we should try and increase the temperature difference as much as possible. This can be seen in equations (3) and (4), where (3) tells us that the molar fraction is the same as the partial pressure and (4) tells us how the partial pressure is varying with the temperature. This can be illustrated in a graph as been done by the Duke students during spring 2010, see Figure 3.

$$\frac{P_i}{P_{tot}} = V_i \tag{3}$$

$$\log_{10} P_i = 7.96681 - \frac{1668.21}{228.0 + T_i} \tag{4}$$

Where:
P_i is partial pressure of water vapor
P_{tot} is total pressure
T_i is temperature
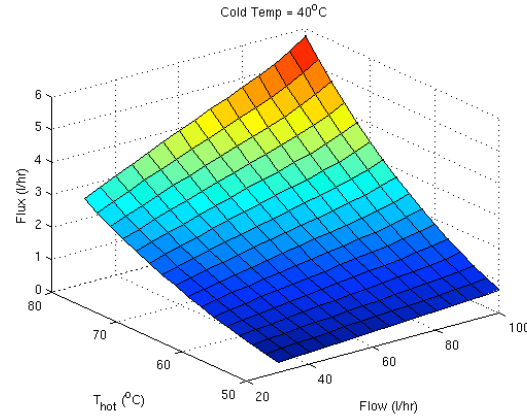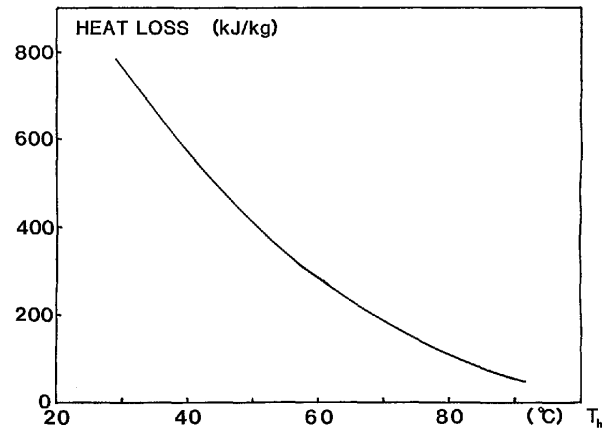V_i is the molar fraction

Figure 3: Flux variation (Eric Esch, 2010)

As the flux increases the energy flow will increase in the system. Although, to get a high yield for a minimum energy input, i.e. a high efficiency, a high temperature difference should be used, as can be seen in figure below.

Figure 4: Heat loss as a function of T_h where T_c is 20[°C] (A.-S Jönsson, 1985)

System layout

Current system layout

The main concept is to have warm dirty water inside the membrane, evaporate it through the membrane, condensing it on the other side, and finally capture it. A schematic drawing below shows how this is done in theory.
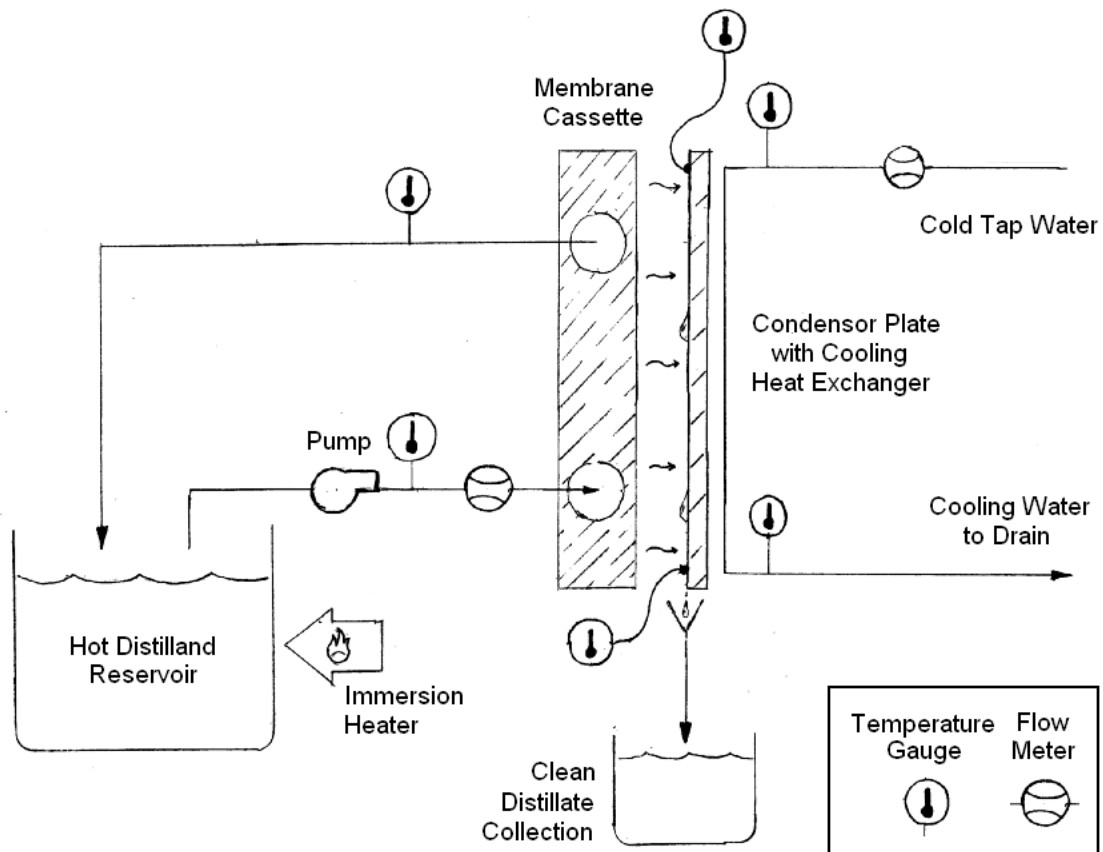
Figure 5: Schematic drawing of membrane distillation unit

Unfortunately the real world is never as beautiful as the theoretical and the prototype can be seen below. It consists mainly of 4 different parts that are marked in Figure 6.

1. Immersive heater with built in pump, flow rates from 60 to 150 l/h, temperatures from room temp and up.
2. Aluminum condenser areas with copper tubing attached with thermal conducting epoxy.
3. Frame with support for lower and upper part of membrane cassette.
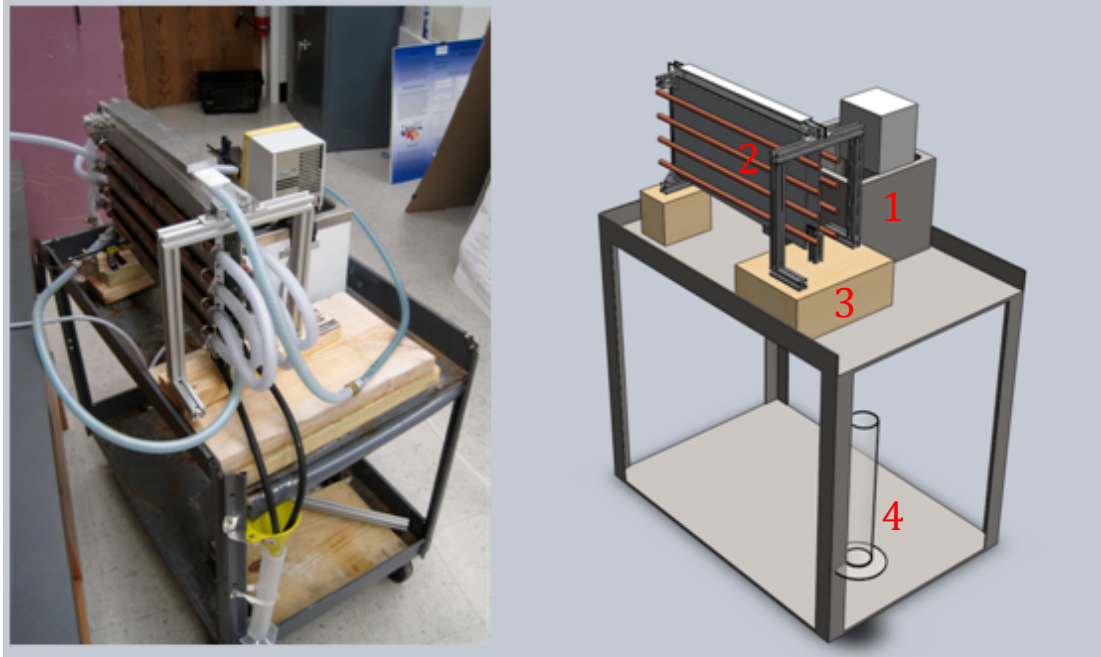4. Fresh water collector

Figure 6: Prototype to the left and Solid works model to the right (Eric Esch, 2010)

The conceptual idea is that the water is heated in the immersive water heater and then pumped by the built in pump up to the membrane, there it enters the membrane from either the top or bottom. Once the membrane is filled with water, the water flows back to the heater for recirculation. The cold side currently takes water from the tap and circulates it through the copper pipes, which in their turn cools the aluminum plates, and finally it flows in to the drain. The condensing plates are fixed with an angle so that when the condensed water has dripped down to the bottom edge it flows out towards the water-collecting bucket.

For more details on the model see the report by the Duke students from spring 2010, (Eric Esch, 2010).

Improvements on current prototype

The current prototype has a very low yield at the optimal running conditions tested by the Duke students the yield was about 100 ml/h, which is about 1/15 of what could be expected from this membrane.

Input conditions	Duke	KTH
Cold water flow	57 l/h	? l/h
Hot water flow	60 l/h	546 l/h
Distance between cooling plates	1"	??? mm
Yield	100 ml/h	1.4-1.9 l/h
ΔT warm water	??	3-5°C

Table 1: Data for two membrane distillation units

Heat exchanger

The cooling plates today are run as a type of counter flow heat exchanger but with the flow first passing one side then the second side, as shown in Figure 7.
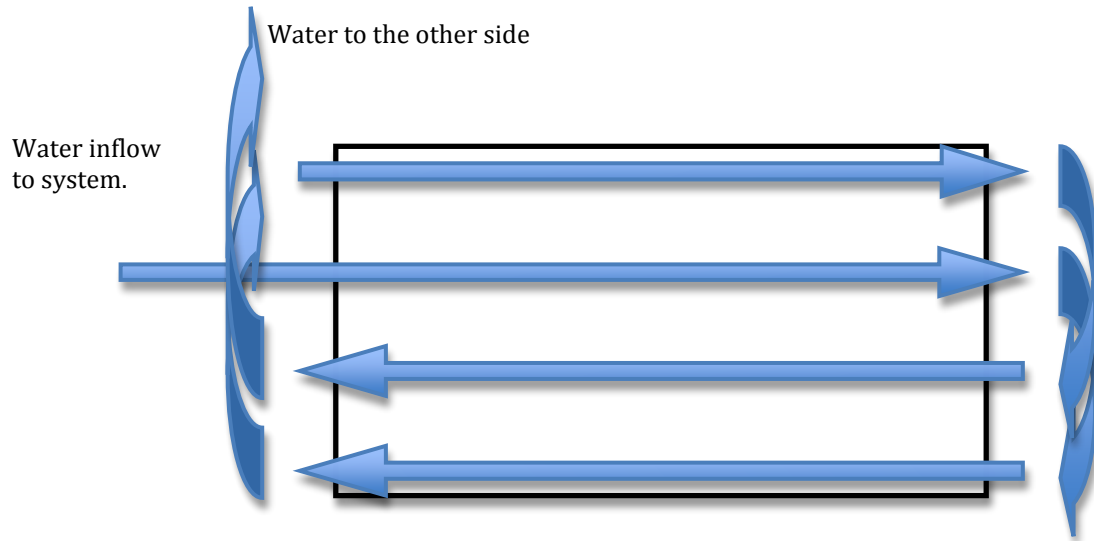
Figure 7: Water flow on cold side current prototype

To gain maximum flux a counter flow heat exchanger should be used, (Alaa Kullab, 2007). We know this due to the fact that the flux is varying with the temperature difference i.e. the bigger the ΔT the bigger the flux. This can also be seen in normal heat exchangers where we know that counter flow heat exchangers gives the biggest energy transfer, (Burghardt, 1986).

In this prototype then it means that the coldest water should enter at the opposite side to the hot water. The membrane is constructed for having the water inflow at the bottom and the outflow on top. To get as equal on each side as possible the water flow will enter on the top left one the be led to the top right one then second from the top on the right over the second on the top to the right and so on, see Figure 8.
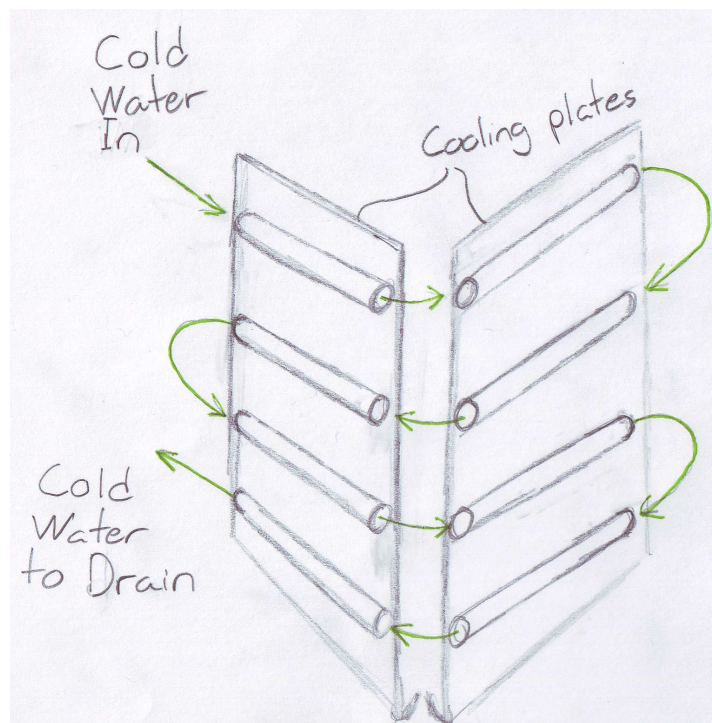

Figure 8: Water flow in new system

The system will be reconfigured so it behaves as a counter flow heat exchanger.

Heat conduction in plates.

The students at Duke did a really nice thermal analysis of the temperature of the cooling plates. In their suggestion the plates would be surrounded by a medium of 70°C and had a heat convective constant of 50 [W/°C m²]. In the report it is also assumed that the temperature of the copper pipes is 22 [°C]. This for the whole plate would give a heat gain of 310 [W], according to equation (5). Although if we analyze the results for KTH we can se that the temperature drop and the water flow in Table 1 suggests that the heat gain should be 950 [W], see equation (6).

$$Q = hA\Delta T \tag{5}$$

Where:
Q is the energy flow [W]
h is a convective constant 50 [W/K m²]
A is the area of the cooling plates 0.129 [m²]
ΔT is the temperature difference set to 48 [°C]

$$Q = \frac{\dot{m}c_p\Delta T}{n} \tag{6}$$

Where:
Q is the energy flow [W]
c_p is the heat capacity of water 4.2 [kj/kg]
$\dot{m}$ is the mass flow of water 0.15 [kg/s]
n is the number of the sides of the membrane that is 2 [-]

How this affects the results is hard to tell, but a less uniform temperature profile is probably one answer. Now, the copper pipes only have a line of conductive contact with the aluminum plates and this gives a small area for the heat to be conducted through.

Therefore a larger area of the copper pipes should be in direct contact with the cooling plates.

Insulation of cooling plates

At the moment no insulation is placed on the outside of the cooling plates, see Figure 9. This causes extra heat gains on the cooling plates that gives a lower temperature difference between the hot water in the membrane and the plates i.e. a lower yield. Also since Durham is a very warm place a problem will be to keep the cooling side cool enough to have a good yield.

Figure 9: Insulation of cooling plates

Therefore insulation should be purchased and placed on the outer surfaces of the cooling plates.

Enclosed volume.

The prototype today is open to the surroundings, which means that water that evaporates through the membrane might continue right out into the surrounding. This is not preferable and is as of this moment the biggest loss in the system. The rig at KTH is sealed from both the sides and from the top. The model at Duke has a semi working seal at the top and no seals on the sides see Figure 10.
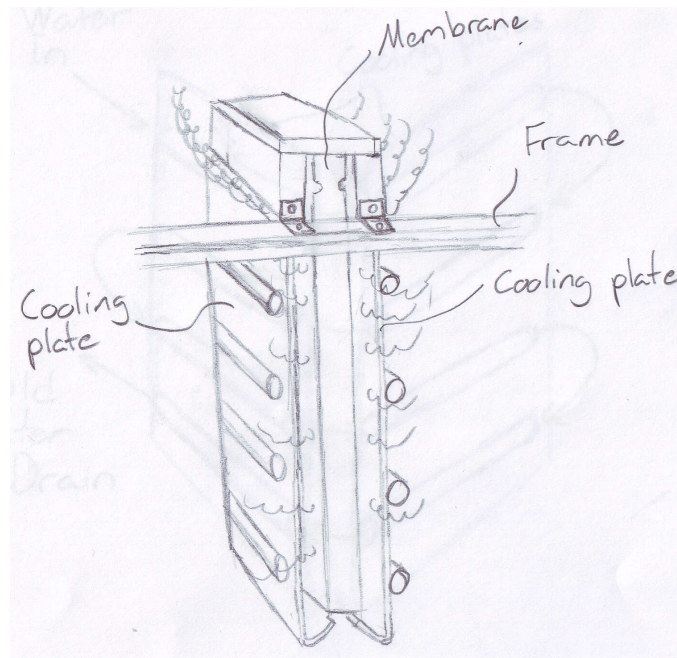

Figure 10: Leakage in current system

Therefore sealing material should be purchased for the sides, preferably some type of cheap plastic material. And design improvements/new design should be made to the top sealing.

Minimize the distance.

As stated earlier, the air gap between the membrane and the cooling plates should be approx 2 [mm]. In the current prototype a much bigger air gap is used. As it could be seen in Figure 2 this distance should be minimized. Construction of the current prototype does not allow small distances between the membrane and the cooling plates for several reasons. Firstly the lower support for the membrane takes up space, see Figure 11.

Figure 11: Cooling plates distance due to lower support

The cooling plates are bent at the bottom for collecting the condensed water, this influences the distance between the cooling plates, see Figure 12.

Figure 12: Distance created due to bending and bolts

In Figure 11-Figure 12 we can also se the bolts that are holding the copper tube in place. These bolts take up a lot of space between the cooling plates.

Therefore the bottom support should be removed, the plates should be re-designed and the bolts should be cut off.

Pumping water.

As seen in Table 1 there is a major difference between the water flow in the system at Duke and the one at KTH. A higher flow rate increases the flux in the system as can be seen in, (Eric Esch, 2010), but it also increases the energy consumption due to a bigger pump. Since the pump is the main energy consumption unit of high-grade energy it is important to keep the size of this as small as possible. The pump used at KTH is a bit extensive, (Baklini, 2010), and since the running parameters will be worse here at Duke an even smaller pump could be used. "Worse," here means that the hot water will be colder and the cooling plates will be warmer.

A pump will also be needed for the system implementation in the duke smart home since the immersive heater would not heat the rainwater.

Therefore a new pump should be purchased and implemented to the system but the immersive heater should still be as heat source for further testing.

Summarized/conclusions

Form the theoretical study we can see that improvements to the current prototype can be made. Although it's not that surprising since the first model was built to make connections between theory and real life.
Ways to improve the yield in the current prototype are:

- *The system will be reconfigured so it behaves as a counter flow heat exchanger.*
- *A larger area of the copper pipes should be in direct contact with the cooling plates.*
- *Insulation should be purchased and placed on the outer surfaces of the cooling plates.*
- *Sealing material should be purchased for the sides, preferably some type of cheap plastic material. And design improvements/new design should be made to the top sealing.*
- *Bottom support should be removed, the plates should be re-designed and the bolts should be cut off.*

Future work

Construct an improved prototype from the suggested improvements.
Make an implementation plan for the MD unit in the smart home.
Validate the water quality for implementation.
Examine the water system and quality in the smart home.

Bibliography

A.-S Jönsson, R. W.-C. (1985). A theoretical Study of Evaporation through microporus membrane. *Desalination 56* , 237-249.

Alaa Kullab, A. M. (2007). *Membrane Distillation and Applications for Water Purification in Thermal Cogeneration - Pilot Plant Trials.* Stockholm: Värmeforsk Service AB.

Baklini, D. (2010, 06 02). Master student working with MD unit at KTH. (J. Larsson, Interviewer)

Burghardt, M. (1986). *Engineering Thermodynamics with Applications - Third Edition.* New York, NY 10022, USA: Harper & Row.

Chuanfeng Liu, A. M. (2005). *Membrane Distillation and Applications for Water Purification in Thermal Cogerneration - A Per-study.* Stockholm: Värmeforsk Service AB.

Eric Esch, J. F. (2010). *Membrane Distillation.* Durham: Duke University Pratt School of Engineering.

Kevin W. Lawson, D. R. (1997). Review of Membrane Distillation. *Journal of Membrane Science* .

L. Martinez, F. G.-D. (2001). Theoretical and experimental studies on desalination using membrane distillation. *Desalination 139* , 373-379.