

MEMBRANE DISTILLATION – A LOW POWER TECHNOLOGY FOR DESALINATION

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INTRODUCTION

In some parts of the world the water supply causes problems because of lack of rain. Unfortunately the available water resources are not sufficient to meet demands. A possibility to improve the situation in coastal regions is to desalt sea water. The principal methods currently used are the thermodynamic ones. One disadvantage of these processes is the high energy consumption. For this reason it is very expensive to supply these systems with regenerative energy. For using sustainable energy, especially for small decentralised systems for the desalination, the energy consumption has to be reduced.

In one project of our institute we are working at the development of a technology with a lower consumption of energy - membrane distillation. The process acts with low energy and heat levels. For this reason, it is possible to use output heat from other processes as energy input. In this project some important influences of the process were studied at a pilot plant on a bench scale.

DESCRIPTION OF THE MEMBRANE DISTILLATION

Membrane distillation is a thermal separation process that can be used for the extraction of clean water. The mass transfer occurs through a porous membrane which is not wettable for the solvent. Two liquids with different temperatures contact the membrane. On the input side (feed side) it is the warm aqueous solution, e.g. sea water, on the effluent side (distillate site) it is the condensed steam diffused through the membrane. The temperature difference between the two liquids causes a steam pressure difference. This steam pressure difference is the driving force for the transportation of steam molecules through the pores of the membrane.

MASS TRANSFER

Figure 1 presents the profiles of the temperature and steam pressure at the membrane.

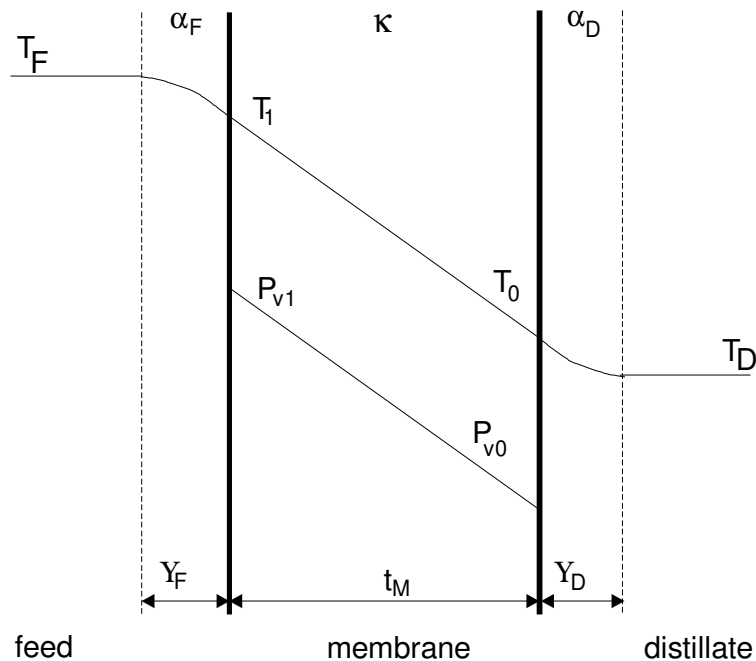


Figure 1: Profile of the temperature and the steam pressure at the membrane considering the temperature polarisation

- T_F (T_D): temperature of the feed (distillate)
 T_1 (T_0): temperature on the feed side (distillate side) at the membrane
 P_{v1} (P_{v0}): steam pressure on the feed side (distillate side) at the membrane
 α_F (α_D): heat transmission coefficient of the boundary film between feed flow (distillation flow) and the membrane
 κ : caloric conductivity of the membrane
 Y_F (Y_D): thickness of the boundary film between feed flow (distillate flow) and the membrane
 t_M : thickness of the membrane

Membrane distillation consists of three different processes:

- steam formation in the solution
- diffusion of the steam through the pores of the membrane
- condensation on the distillate side

Between the mass flux density j_m and the steam pressure difference ΔP_v of the water there is a linear connection (for aqueous solutions and $\Delta T = (T_1 - T_0) < 20$ K)

$$j_m = c \cdot (P_{v1} - P_{v0}) = c \cdot \Delta P_v = c \cdot \Delta T \cdot \frac{P_v \cdot H \cdot M}{R \cdot T_m^2}$$

T_m : mean temperature $T_m = (T_1 - T_2)/2$

c : transportation coefficient of the membrane for steam (depends on the structure of the membrane (size of the pores, thickness, porosity and the medium))

H : enthalpy of vaporisation ($H = 2256$ kJ/kg)

M : molar mass of water ($M = 18$ g/mol)

R : gas constant ($R = 8,31$ J · K⁻¹ · mol⁻¹)

The steam pressure of the water increases exponentially with increasing temperature. This means that the driving force for the membrane distillation also enlarges exponentially with the increasing mean temperature.

The temperatures of the feed or distillate volume flow T_F and T_D are not identical to the temperatures T_1 and T_0 at the membrane because of the flow in the boundary film. The difference between $(T_F - T_D)$ and $(T_1 - T_0)$ is called “temperature polarisation” and is described by the temperature polarisation factor τ .

$$\tau \cdot (T_F - T_D) = T_1 - T_0$$

τ has the value 1 if there is no temperature polarisation and the value 0 if the temperature difference declines completely in the boundary film on both sides of the membrane.

The temperature polarisation factor τ depends on the thickness of the boundary film and therefore from the state of the flow at the membrane.

MEMBRANES

Membrane distillation is limited to the use of hydrophobic, micro-spongy membranes. They mostly are produced from polytetrafluorethylene (PTFE), polypropylene (PP) or polyvinylidene fluoride (PVDF).

Membranes with the pore diameter 0.01-1.00 mm can be used for the membrane distillation. Two factors must be considered for the choice of the pore diameter:

the pores must be large enough to allow a mass flow and but small enough to prevent intrusion of water under operating conditions. The flow through a pore depends on the average pore diameter of the membrane, the membrane porosity and the thickness of the membrane.

There is a relationship between the maximum pore size of a membrane and the maximum permissible pressure difference.

1. With increasing steam pressure at the feed side no liquid passes through the membrane till the pressure difference ΔP_{\max} is achieved.
2. From this point, the liquid begins to penetrate into the largest pores and has the possibility to pass the membrane. If the pressure of the feed side further increases, the liquid seeps into more and more pores and the flow increases.
3. If the pressure of the feed side drops again, the flow will be reduced.

Wet pores allow the liquid to pass the membrane directly. This can cause a series of problems. The contaminated solution on the feed side can reach the distillate side without obstruction and causes a contamination of the distillate. In the literature a maximum pore radius of 0.5 – 0.6 mm is recommended, in order to prevent that the difference of the pressure ΔP_{\max} is not exceeded on account of the pressure of the feed side.

DESCRIPTION OF EXPERIMENTS

5.1 Experimental Plant and Devices

The following scheme shows the experimental plant which was used for the measurements. The experimental arrangements are represented schematically in Figure 2.

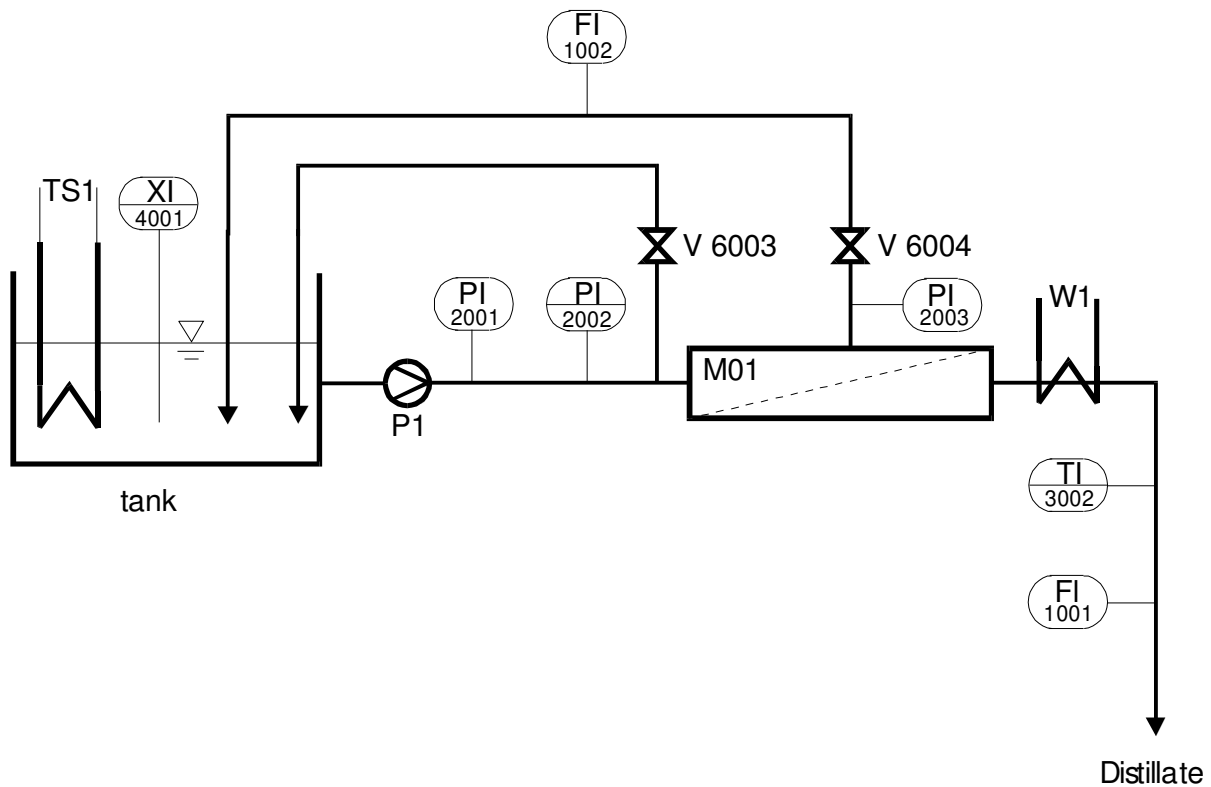


Figure 2: Scheme of the experimental plant

The solution in the tank is heated up to operating temperature by the immersion heater TS1. The conductivity measuring instrument XI 4001 allows a continuous check of the operating temperature and of the conductivity of the solution.

The variation of the pressure and the volume flow through the membrane can be controlled by the valves V 6003 and V 6004. The overpressure of the feed side is displayed at the pressure gauge PI 2001.

The concentrate volume flow is determined with the flow meter FL 1002. The flow meter FL 1001 shows the distillate volume flow. Furthermore, the volume of the distillate is determined by the mass and density after cooling to room temperature (20 °C).

The test membranes are inserted into the test cell M01. The effective membrane surface in the module is 80 cm². Between the lower part of the channel of the test cell and the membrane there is a spacer of wire netting.

The temperature of the volume flow of the feed T_F is adjusted in the tank. For the determination of the temperature T_D of the distillate at the backside of the membrane a temperature dependent resistance TI 3002 is fixed at the underside of the membrane module. The temperature difference at the membrane is maintained constant by a control system on the module top face with an error of ± 2 °C.

The experimental plant is represented in Figure 3.

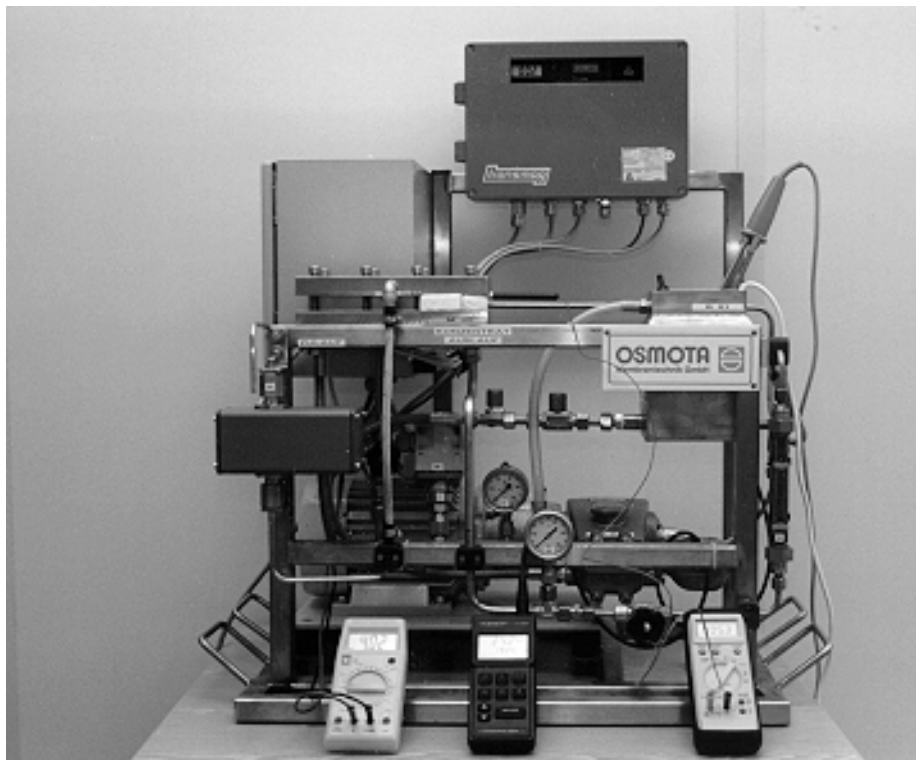


Figure 3: Experimental plant

TESTING REALISATION

During the investigations, membranes of different companies were tested varying temperature of the feed, pressure of the feed side and flow rate passing the membrane.

At these experiments, the burst pressure of the membranes is considered and a low overpressure on the feed side $P_{\dot{U},F}$ is adjusted accordingly.

During the experiments the temperature difference ($T_F - T_D$) is kept constantly with 14 °C. Bi-distilled water is used as feed solution. For the experiments for the determination of salting support a saline solution with 35 g NaCl/l is used. The maximum temperature of the feed is 80 °C.

In Table 1, the used membranes with their most important qualities are presented.

Table 1: Used membranes

Manufacturer	Gore	Gore	Akzo Nobel	Akzo Nobel
Material	PTFE	PTFE	PP	PP
Base material	PP	PP	PP	PP
Diameter of pores [μm]	0.02	0.1	0.1	0.2
Porosity [%]	75*	75*	67*	67*
Thickness [μm]	50*	50*	160	160

* asked by telephone from the manufacturer

EXPERIMENTAL RESULTS

Flow through the PTFE membranes depending on the overpressure of the feed side

In these experiments the main question is how the pressure at the feed side affects the distillate flow through the PTFE membranes. Bi-distilled water is used in the tank. In Figure 4, the experimental results for a membrane with a pore diameter of 0.1 μm and temperatures of the feed $T_F = 60/70/80$ °C are represented.

By the ascent of the temperature of the feed from $T_F = 60$ °C to $T_F = 80$ °C the mean temperature and therefore the steam pressure difference between the feed and the distillate side of the membrane increases. The result is an increased flow. The absolute pressure of the feed side has no influence on the flow up to an overpressure of $P_{\text{Ü,F}} = 2.5$ bars, because the partial pressure of steam is independent of the pressure. The driving force at the membrane distillation, the steam pressure, keeps constant.

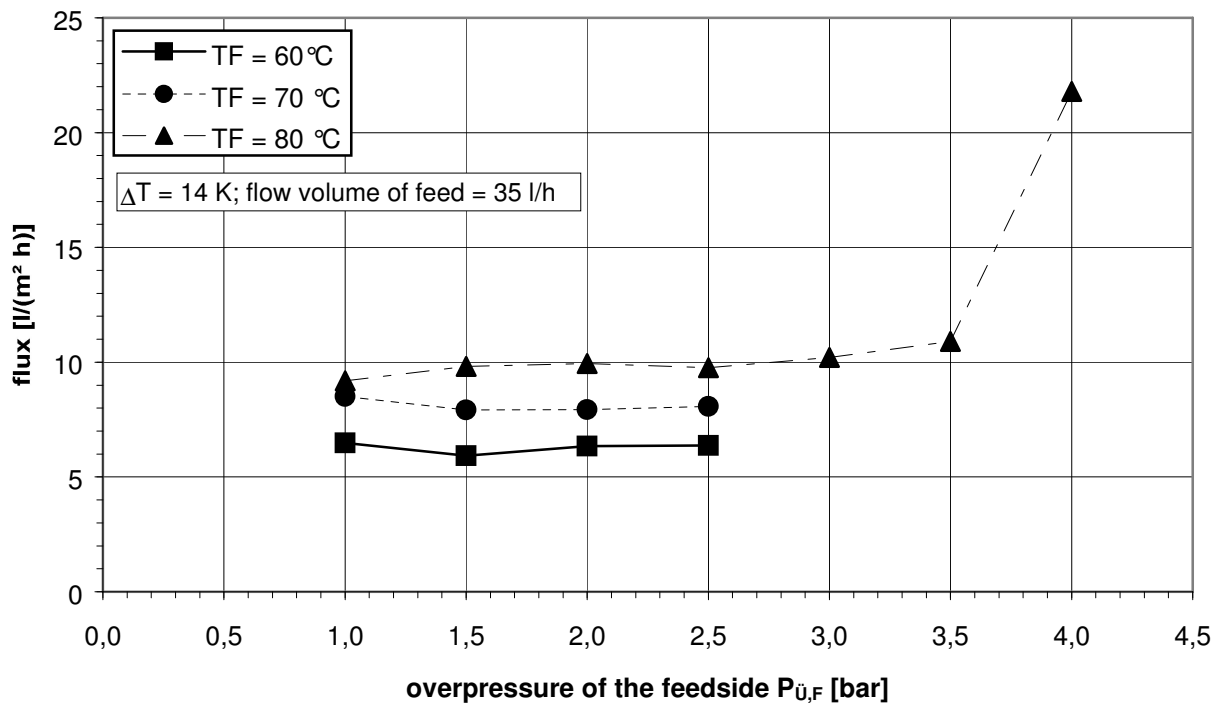


Figure 4: Flow through a PTFE-Membrane with a pore diameter of 0.1 µm in dependence of the overpressure on the feed side $P_{\ddot{U},F}$

The ascent of the flow at $P_{\ddot{U},F} = 4$ bars is the result of water penetrating into the pores of the membrane because of the maximum permissible pressure difference ΔP_{\max} on the feed side. The membrane is wetted and the solution pours directly through the pores. The burst pressure is exceeded.

After reaching the burst point the membrane is dried and inserted again. Now the flow at an overpressure of $P_{\ddot{U},F} = 1$ bar is higher than with an unused membrane. This shows that the membrane is damaged irreversibly because of exceeding the burst pressure. The reason may be an enlargement of the pore diameter because of the mechanical load. The result is a lower maximum permissible pressure difference ΔP_{\max} .

There were also experiments done with a PTFE - membrane with a pore diameter of 0.02 µm. On account of the smaller pore radius resulting in a less transportation coefficient at all temperatures the flow is lower than with the membrane with the diameter of 0.1 µm.

Comparison of membrane materials, PTFE and PP, at different temperatures in the tank

In Figure 5, the flow of all membranes tested is presented for an overpressure of $P_{\bar{U},F} = 1$ bar on the feed side and a volume stream of the feed of 35 l/h, compared with the pore diameter. The temperature of the feed T_F is 60, 70 and 80 °C for all membranes. The measured values in the case of a feed temperature T_F , the same membrane material, however different pore diameters, are combined with a line.

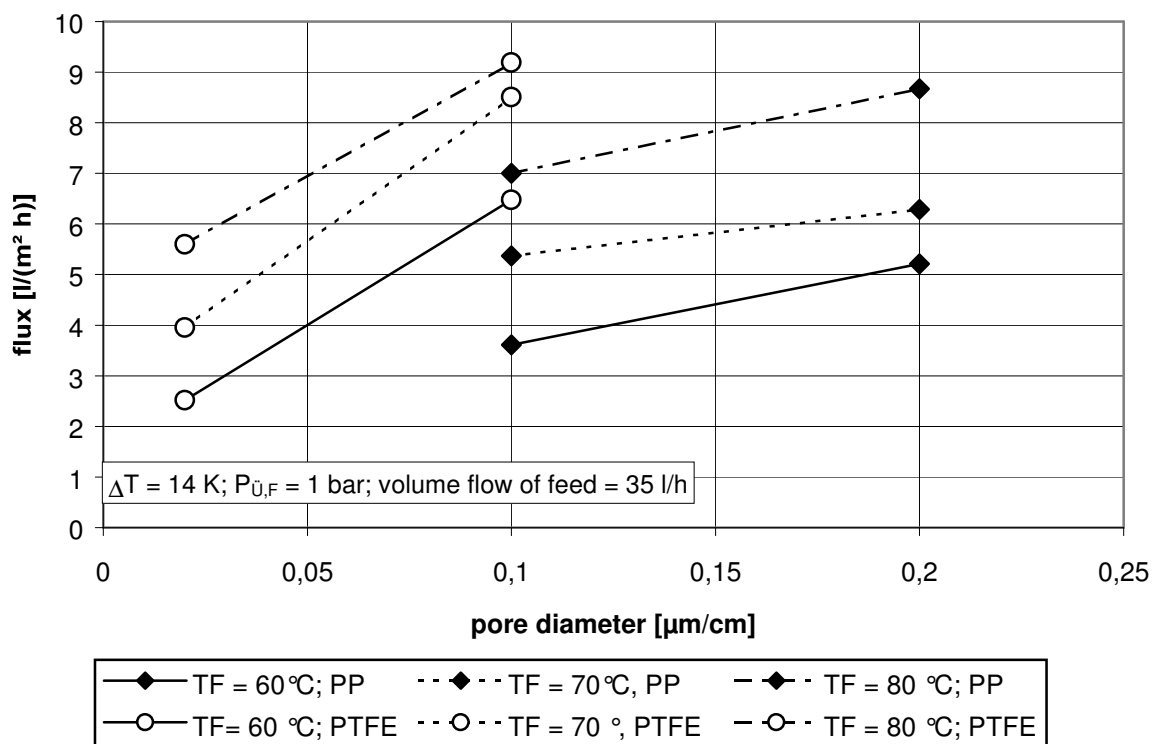


Figure 5: Comparison of the flux depending on the pore diameter and the material of the membrane

On the one hand, the flow through the PP membranes depends on the feed temperature and on the other hand on the pore diameter. For a constant temperature, the flow is lower at smaller pore diameter than at larger pore diameter. The difference compared to the PTFE membranes is smaller because the pore diameters differ from each other around a factor of 2. At the membranes of PTFE the diameter of the pores differs around a factor of 5.

From a comparison of membranes with same pore diameter from PTFE and PP, it can be recognised that the flow through the PTFE - membrane at all temperatures is higher than through the PP membrane. The steam can diffuse through the PTFE membrane more easily because the membrane is thinner and the porosity greater than at the membrane of PP.

Flow depending on the volume flow over the membrane

The flow through the PTFE membranes in comparison with the volume flow of the feed and the corresponding Reynolds number is presented in Figure 6.

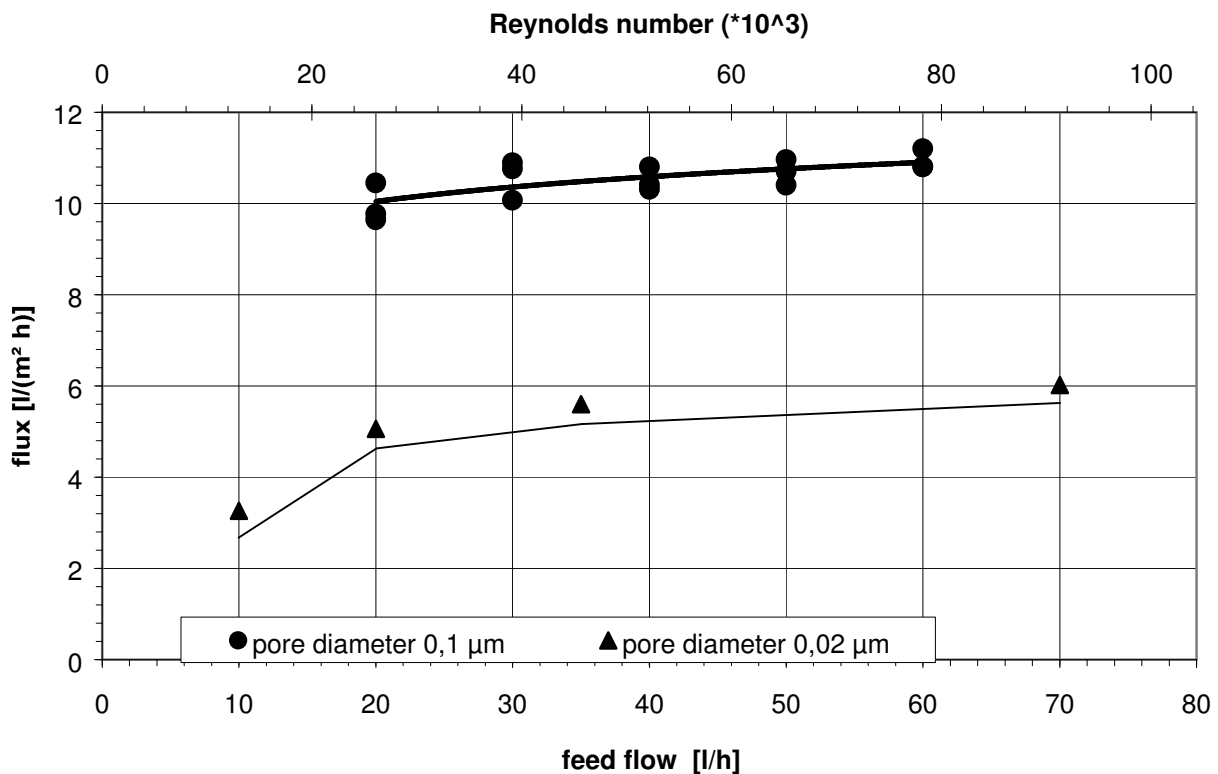


Figure 6: Flow through a PTFE-membrane compared with the volume flow and the Reynolds number

It can be recognised that the flow at both membranes increases slowly with increasing volume flow. The reason for this is the flow situation.

In a system with rectangular cross section, the flow in the case of low Reynolds numbers initially is laminar. After reaching a specific flow velocity the laminar flow becomes turbulent. The result is an intensive mass transfer in the medium.

This fact is described by the Reynolds number. The critical Reynolds number for a system with rectangular cross section is 2320. If the Reynolds number becomes larger than 2320 the laminar flow changes over the state of transition into the turbulent field. The Reynolds number is calculated as follows:

$$\text{Re} = \frac{w \cdot d_h}{\nu}$$

where:

w: flow velocity

ν : kinematic viscosity of fluid

d_h : hydraulic diameter of the flow system

In this case the flow is under the critical Reynolds number of 2320. The reason is the spacer between the lower part of the channel and the membrane. With increasing volume flow, the flow changes in the turbulent field.

In the transition region between laminar and turbulent flow, the boundary film becomes thinner and achieves the minimum in the case of turbulent flow. The effective temperature difference at the membrane $T_1 - T_0$ increases and the temperature polarisation decreases. As a result, the steaming pressure difference and therefore the driving force for membrane distillation increases. The distillate flow goes up and achieves its maximum in the case of turbulent flow.

These facts are the same for both membranes, but the membrane with a pore diameter of 0.02 μm has a smaller flow because of the discussed reasons.

Salt support of the membranes

In the previous experiments pure water was on both sides of the membrane. The aim of the distillation for this application is the desalination of sea water. Therefore in the next experiments the salt support of the membranes is tested. The saline solution in the tank has a concentration of 35 g NaCl/l (mean total salinity of sea water). The conductivity of the solution in the tank is 50.4 mS/cm.

In Figure 7, the flow and the conductivity of the distillate compared with the overpressure at the feed side is presented.

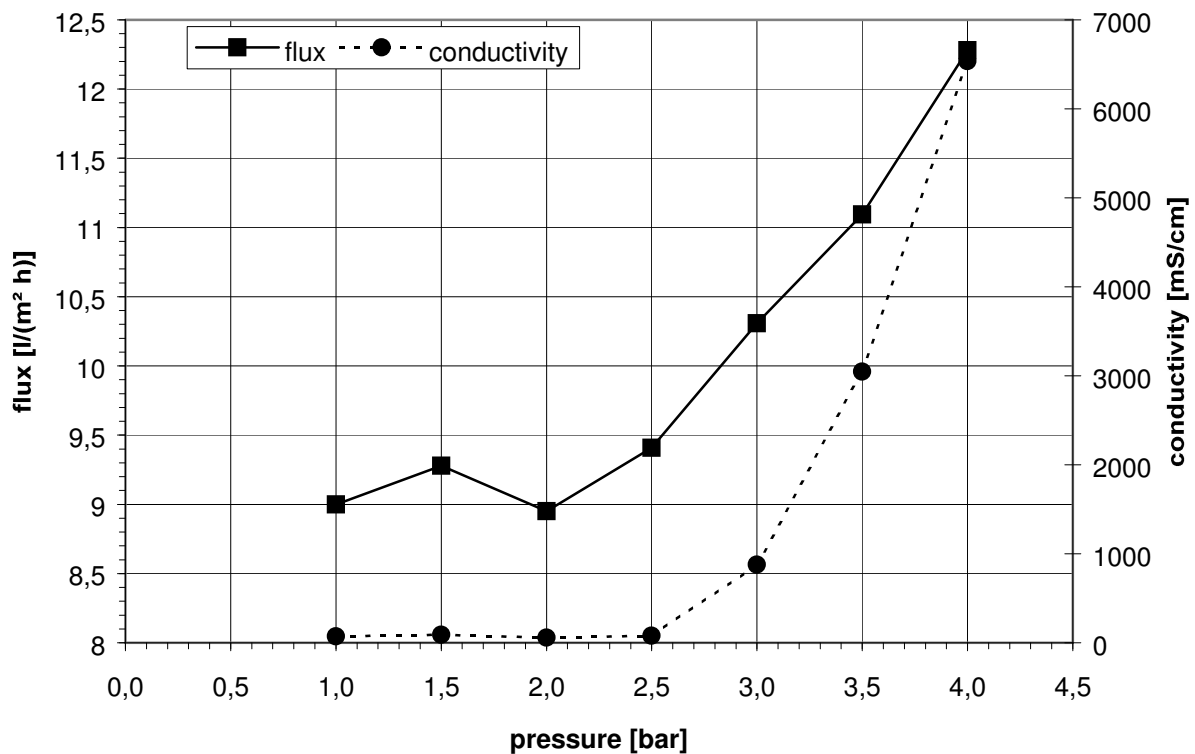


Figure 7: Flow and conductivity in dependence on the overpressure $P_{Ü,F}$ of the feed side at a PTFE-membrane with a pore diameter of 0.1 μm

From an overpressure of $P_{Ü,F} = 3$ bars of the feed side, flow and conductivity increase because the solution penetrates into the pores.

Conductivity up to $P_{Ü,F} = 2.5$ bar has to be lower because this is a distillation process. Perhaps there is a bigger diffusion through the membrane because of the high temperatures of the feed $T_F = 80$ °C. The value is very low, compared with the permissible boundary value for conductivity in the German law for drinking water regulation of 2000 $\mu\text{S}/\text{cm}$ (e.g. the conductivity of tap water at Hanau is 451 $\mu\text{S}/\text{cm}$).

The absolute pressure on the feed side has no influence on the flow and conductivity of the distillate. Only if the maximally permissible pressure difference ΔP_{max} is exceeded, there is the burst of the membrane and flow as well as conductivity of the distillate increase.

In Figure 8, the flows through the membranes of PTFE and PP in the experiments with salt solution and bi-distilled water are presented.

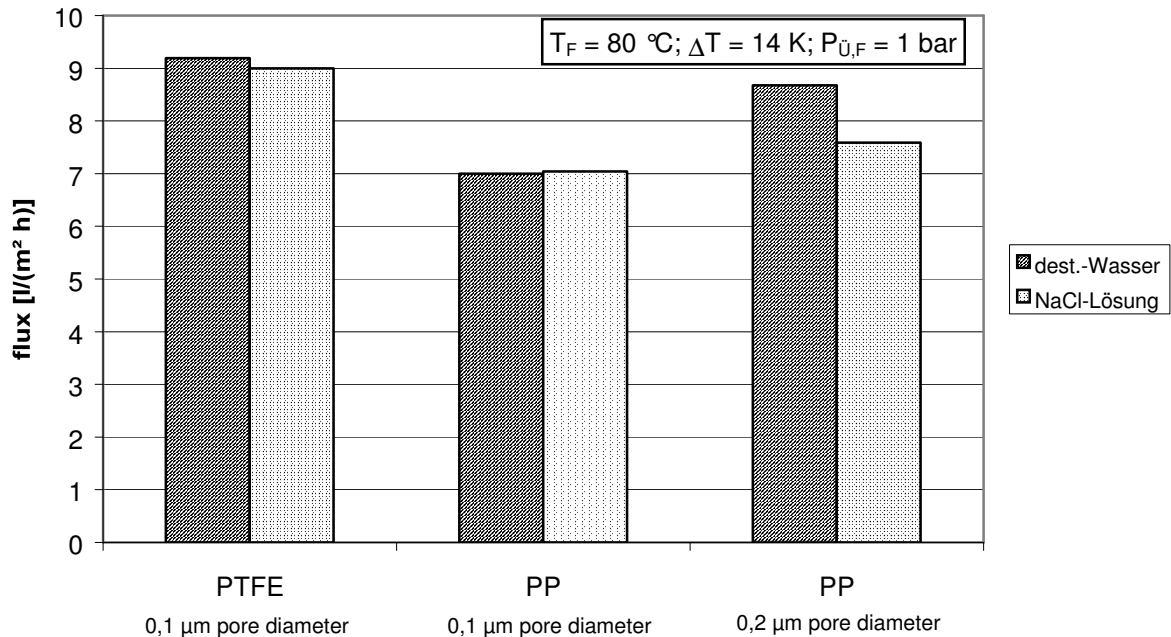


Figure 8: Flow in dependence on the solution in the tank

The difference of the distillate profit at the different membranes is very small. The influence of salt concentration on the flow can be neglected. The salt in the solution is not important during the formation of the steam pressure difference. The steam pressure of the NaCl-solution at 80 °C is theoretically 0.001 bar smaller than the steam pressure of pure water. A divergence of the flow of 1.1 l/(m² H) is not important for a constant temperature of the feed and constant temperature differences.

Remarks on the membrane distillation with sea water

A fact of membrane distillation is that the higher the feed temperature and temperature difference, the higher is the distillate flow.

However, with desalination of sea water, precipitation or deposits which may block the membrane (membrane scaling) may occur. Therefore, the operating temperature during membrane distillation is to a maximum of 80 °C, relatively small compared to other thermal procedures. With further increase in temperature, there would be an increased fall out of heavy soluble combinations

as calcium carbonate (CaCO_3), calcium sulphate (CaSO_4) and magnesium hydroxide ($\text{Mg}(\text{OH})_2$).

The dephlegmation of sea water is very small. The volume of the feed is of about 40 times larger than the distillate flow. Therefore, no salts turn out on account of the increase of the salinity. In practice, the salt concentration should not exceed 7%, if the concentrate flows through the membrane modules several times, or if it is reduced with sea water.

USE OF REGENERATIVE ENERGY FOR MEMBRANE DISTILLATION

Membrane distillation needs on the one hand energy for warming up the sea water to a temperature between 60 – 80 °C. On the other hand, electric energy must be provided.

For energy supply, the use of regenerative energy is very practical because the solar radiation offer is often very big in areas with water shortage.

In the next section, the possible application of thermal solar collectors and photovoltaics for a membrane distillation plant for water desalination is discussed.

Use of thermal solar collectors

Low temperature collector systems are used for warming the water up to a temperature of 80 °C.

1. Building and function of low temperature collector systems

In Figure 9 a low-temperature collector system is presented.

A flat collector essentially consists of absorber, translucent covering, casing and insulation. The absorber is used for the transformation of short-wavelength radiation in heat. This function takes on an absorber material with as high as possible absorbing power in the spectrum of visible light. Conversely a low absorption- and therefore emissive power in the spectrum of the heat radiation must be aimed for. The absorber should allow a good thermal conduction to the heat transfer medium. The translucent covering of a collector should be as leaky

as possible for solar radiation, but retain the long-wave thermal reflection of the absorber. It is necessary to minimise the convective heat loss to the environment.

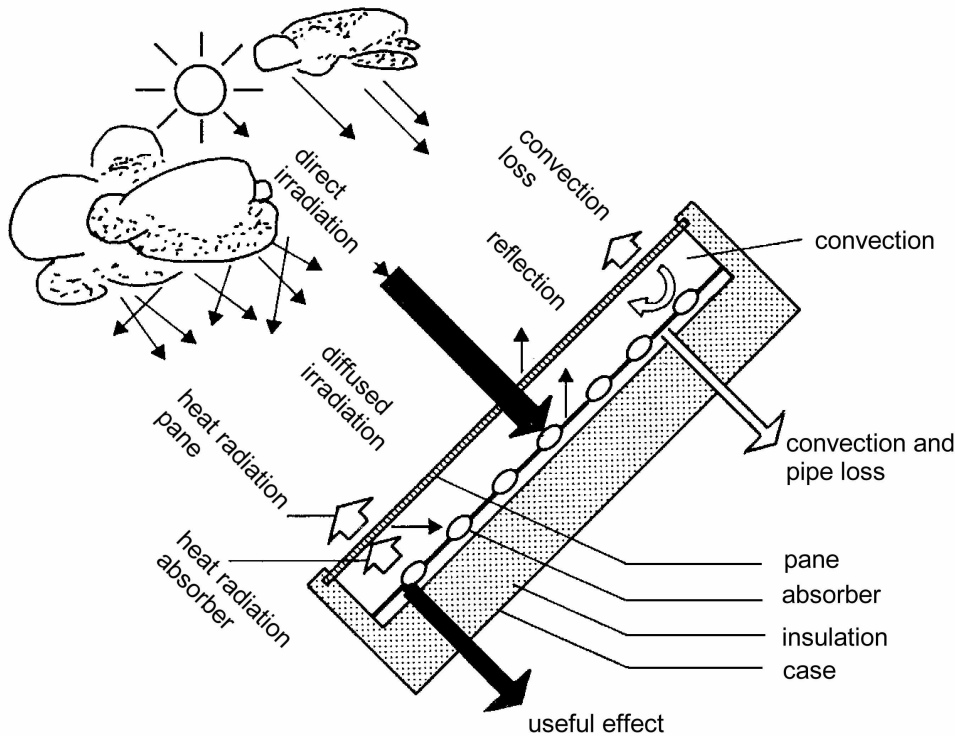


Figure 9 : Building and function of a flat low temperature collector system

2. Description of different low temperature collector systems

There are three important low temperature systems in the field of low temperature collector systems:

- tube absorber
- flat collectors and vacuum flat collectors
- vacuum tube collectors

Tube absorbers exist in the simplest case of black, UV - resistant and flexible tube lay on a horizontal space. The result of no heat insulation is a high heat loss and therefore low efficiency. On account of the simple construction, the price is low (100 - 200 DM/m²).

In the flat collector (Figure 9), measures are taken to reduce heat loss (glass cover in front for greenhouse effect and heat insulation on the reverse side). In

order to reduce the convective heat losses from the absorber to the covering, the space between both is evacuated at some models. This system is called vacuum flat collector. With these measures, higher operating temperatures are reached without essential higher heat losses. The costs are between 500 to 800 DM/m²:

In vacuum tube collectors, the interior can be evacuated to even lower pressures. In this way, convection and transmission losses are excluded nearly completely. Only heat radiation occurs as a dissipation factor. This is minimized by selective coating of the absorbers. The costs of the vacuum tube collectors are between 1000 and 2000 DM/m².

3. Selection of a collector model

The experiments have shown that the distillate flow strongly depends on feed temperature T_F . There is an optimum for feed temperature from $T_F = 80$ °C. Therefore, for membrane distillation all collectors can be used which are able to increase the temperature of the solution by about 60 K compared to ambient temperature T_U .

Tube absorbers are not able to increase the temperature of the feed solution up to 60 K compared to ambient temperature because of their high heat losses.

It is important that, not only with high, e.g. 1000 W/m², but also in the case of smaller exposure rates, e.g. 600 W/m² and a temperature difference of 60 K between the temperature of the absorber T_A and the ambient temperature T_U , the efficiency of the collector is large enough to warm up the feed solution to the required working temperature of 80 °C.

In general for tube collectors, if the temperature difference between the absorber and the environment cannot reach the required 60 K, the low efficiency cannot be compensated through an enlarged collector face. The sea water cannot be warmed up to required 80 °C and the distillate flow is reduced. The use of cheaper flat collectors compared to more expensive vacuum flat or vacuum tube collectors is limited.

Use of photovoltaics

The electricity demand for the membrane distillation for energy is small compared to the thermal one. Highest energy consumer is the sea water dredging pump. The electrical demand for energy depends on lifting height and distance of the sea water, the volume flow as well as the pressure losses.

Electrical energy can be provided by photovoltaics. This is especially good for plants in which the sea water is warmed up by solar thermal collectors, because there is always a lot of electrical energy available when a lot of heated water must be moved.

SUMMARY AND PROSPECTS

The experiments supplied the following results:

1. The distillate flow through the tested membranes depends on the feed temperature and the pore diameter of the membrane. The pressure of the feed side has no effect. It has to be noted that if the burst point is exceeded once, it can cause non-reversible damage of the membrane. In this case the raw solution can pass the membrane directly and contaminate the distillate. Therefore, for the planning of the system it is necessary to range under the burst point.
2. Further on it is discovered that the flow rate is higher using membranes of PTFE than at membranes of PP. Pressure loading capacity is also higher at the PTFE membranes.
3. Salt support is very good at all tested membranes with a conductivity from less than 100 $\mu\text{S}/\text{cm}$ in the distillate, well below the required boundary values.
4. In order to achieve a higher distillate flow, the flow of the feed solution should be turbulent along the membrane.
5. The use of the solar energy for membrane distillation is practical on account of the relatively low temperature levels and the high solar radiation in the likely areas of application.
6. For using the membrane distillation in the practice, it is necessary to do further studies, especially in pilot-plant and commercial scale.

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