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Simultaneous production of high-quality water and electrical power from aqueous feedstock's and waste heat by high-pressure membrane distillation

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ABSTRACT

A new membrane distillation (MD) concept (MemPower) has been developed for the simultaneous production of high-quality water from various aqueous feedstocks with cogeneration of mechanical power (electricity). Driven by low-grade heat (waste, solar, geothermal, etc.) a pressurized distillate can be produced by operating TNO's Memstill® process at high hydraulic pressures. These pressures are theoretically limited by the liquid entry pressure (*LEP*) of the membrane. The proof of principle has been shown and is based on the transport of water vapor against a hydraulic pressure gradient. Various commercially available membranes have been evaluated in order to obtain high yields in water flux and power densities. Power densities have been measured which are sufficient to drive the pumps in MD. This allows standalone Memstill® units without electricity consumption to be possible, which are fully driven by waste heat. The application of new incompressible hydrophobic membranes, combining a high permeance with a high *LEP*, will allow for much higher power densities.

Keywords: Low-grade heat; Waste heat; Solar; Desalination; Drinking water; Heat–water networks; Power; Liquid entry pressure; Membrane distillation; High pressure

1. Introduction

Due to growth in world population and rising welfare, there is a strongly increasing demand for both clean water and energy. The availability of these primary resources is under pressure due to increasing urbanization, climate change (drought, salinization, greenhouse effect), and more strict standards for emissions of chemicals and thermal energy.

A new concept, so-called MemPower, connects both worlds. Here, low-grade heat (e.g. waste heat, solar heat, etc.) is used for both production of fresh/clean water from (impure) aqueous streams and for generation of high-value energy by work/electricity. By producing a pressurized distillate in membrane

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distillation (MD), MemPower promises to be a potential cross-sectorial integral technology for the water and energy markets.

In this paper, the proof of principle of this new concept will be evaluated. First, the principle of MemPower is discussed as well as the differences with other types of energy-from-water production (Blue Energy). Next, the experimental setup(s) and procedure are explained. Then, the experimental validation of the simultaneous production of water and power will be evaluated. Finally, some potential applications of technologies based on this principle are suggested.

2. Principle of MemPower

MemPower is a new concept to produce a pressurized distillate in MD. If this concept is applied to a specific MD technology in general (see [1]), or TNO's Memstill® process in particular [2], it can be used to produce pure water and power from low-grade heat and aqueous feedstocks.

The principle of MemPower is visualized in Fig. 1. An aqueous feedstock (e.g. seawater) is heated, e.g. by utilizing low-grade heat. This heated feedstock at temperature T_2 is separated by a hydrophobic porous membrane from a cooler distillate of temperature T_3. This temperature difference results in a gradient in water vapor pressure across the membrane. Therefore, water evaporates near the membrane at (2), the water vapor diffuses through the pores of the membrane toward the distillate section (3) where it recondenses near the membrane. The hydraulic (absolute) pressure of the distillate increases toward a value p_{total} by throttling of the effluent valve in the distillate.

This process continues, i.e. the hydraulic pressure increases, as long as a driving force for evaporation and condensation exists due to a difference in temperature (vapor pressure) between feed and distillate, provided that the hydraulic pressure of the distillate remains below the so-called breakthrough pressure of the membrane. Above this pressure, also called the Liquid Entry Pressure (*LEP*), the pores are wetted, causing liquid water to flow back via the membrane from the distillate side toward the feed. The pressurized distillate can be used to drive a turbine to generate hydropower. The electrical power density (*PD*), expressed in W m^{-2} membrane, equals the product of turbine efficiency η, volumetric flux of distillate (in $\text{m}^3\,\text{m}^2\,\text{s}^{-1}$), and the hydraulic pressure p_{total} of the distillate (in Pa):

$$PD = \eta \varphi_{\text{distillate}}\ p_{\text{total}} \tag{1}$$

The smaller the pore diameter, the higher the maximum *PD* as indicated in Fig. 2. Rewriting of this equation gives a relation for the specific power production per m^3 distillate:

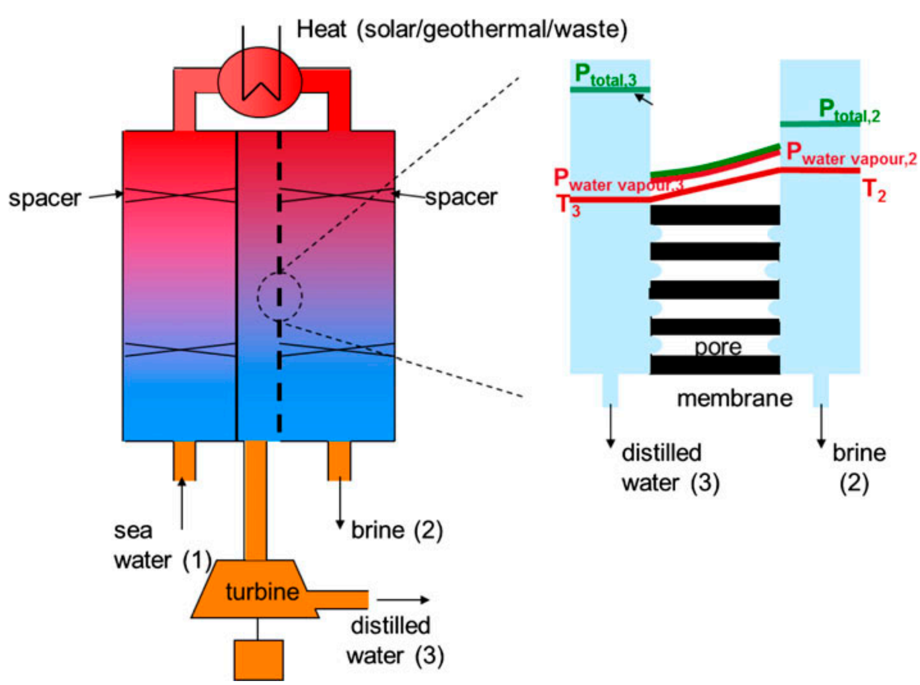

Fig. 1. Principle of MemPower (right) and its integration in TNO's Memstill® process (left, [2]).

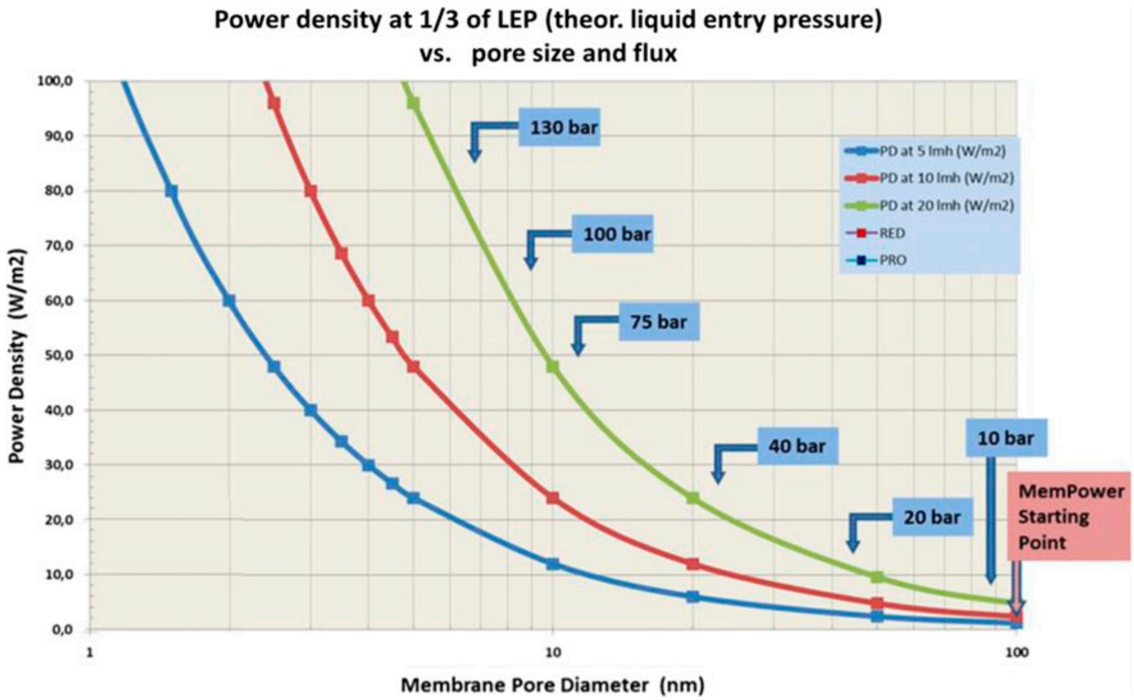

Fig. 2. Perspective of MemPower in dependency of distillate flux and pore diameter. The lines are calculated with Eq. (1) using $B = 1$, $\gamma = 58.0$ mN m^{-1} (i.e. the surface tension of water at 100℃), $\cos\theta = 1$, and $\eta_{\text{turbine}} = 0.9$.

$$\frac{PD}{\varphi_{\text{distillate}}}\left(\frac{\text{J}}{\text{m}^3}\right) = \eta p_{\text{total}} \qquad (2)$$

For a total hydraulic distillate pressure of 10 bar, this specific power is, therefore, about 1,000 kJ m^{-3} distillate (= 1 MJ m^{-3} distillate = 1 kJ.kg^{-1} distillate).

Fig. 2 shows the maximum *PD* for three different values of the distillate flux (5, 10, and 20 L m^{-2} h^{-1}) assuming a distillate hydraulic pressure of *LEP*/3 and a cylindrical pore with a diameter as indicated on the *x*-axis. *LEP* can be calculated with the Young-Laplace equation:

$$LEP = \frac{2B\gamma \cos\theta}{r} \qquad (3)$$

with B a geometrical constant, γ the surface tension of the liquid contacting the pore (here: distillate), ϕ the contact angle, and r the pore diameter.

Assuming its principle to work, it is expected that potential power densities of 10–30 W m^{-2} could be possible.

3. MemPower relative to Blue Energy

In the Water–Energy domain, various other technologies are investigated. A recent overview has been published in Nature [3]. In contrast with MemPower, these technologies are not driven by low-grade heat, but by the chemical energy which is present in water due to the (dissolved) species i.e. organic compounds and ions. Focusing on the latter (Blue Energy), electrical energy is generated from the difference in salt concentration of salty and sweet water. Drawback, however, is that a wastewater stream (brackish water) is created whereas a fresh water stream is consumed. Therefore, Blue Energy is characterized by energy *from* water. Currently, two types of Blue Energy exist, i.e. Reversed Electro Dialysis (RED) and Pressure Retarded Osmosis (PRO). Table 1 gives an overview of the characteristics of MemPower and Blue Energy.

4. Experimental setup and procedure

Several test setups and test procedures are used for evaluating the potential of performing MD at elevated distillate pressure. Various commercially available membranes are evaluated which are named A, B, C, etc. because of confidentiality. During the research, the experimental setup has been changed/modified two times:

- Setup 1: directed at first proof of principle, no distillate circulation, P_{max} = 5 bar.

Table 1
Characteristics of MemPower and Blue Energy

Characteristics	MemPower	PRO and RED (Blue Energy)
Products	Fresh water *and* electricity	Electricity *from* consuming fresh water
Energy potential	Potential >10 $W_e\,m^{-2}$	Current: 1 $W_e\,m^{-2}$ (potential: 5 $W_e\,m^{-2}$)
Pretreatment of feedstock	Simple pretreatment	Excessive pretreatment
Types of feedstocks	All types of feed water	Mixing high- and low-salt water streams
Driver	Works on low-grade heat (CSP)	No need for heat (no synergy with CSP)
Application area	Stand alone in arid areas	Delta oriented

- Setup 2: direct contact membrane distillation (DCMD), P_{max} = 10 bar.
- Setup 3: adaptation of Setup 2, P_{max} = 22 bar.

4.1. Setup 1: first proof of principle, no distillate circulation, P_{max} = 5 bar

For obtaining a first proof of principle an existing standard test cell for determination of *LEP* of membranes was used, see Figs. 3 and 4. The membrane interfacial area = 28 cm^2.

The mode of operation was as follows: a test solution (demineralized water with about 2 $g\,l^{-1}$ added sodium chloride) was heated to a temperature of about 80˚C, and circulated through the feed chamber, at a pressure around 0.2 bar. In this feed chamber, a double feed spacer was placed: a normal non-woven polypropylene (PP) netting with a thickness of 2 mm (Delstar), and between this and the membrane a thin-woven stainless steel SS316 mesh was mounted with a with pore size of 13 μm (Dinxperlo Gaasweverij).

The lower side of the test cell (distillate chamber) was kept in a bath of melting ice, because here no circulation was possible (dead-end discharge of distillate). The distillate discharge tube was filled with demineralized water and closed, and the hydraulic pressure measured.

4.2. Setup 2: DCMD, P_{max} = 10 bar

After the first proof of principle, a test system was constructed aimed at evaluation of various membranes and spacer materials at similar DCMD conditions. Fig. 5 shows a picture of this Setup 2.

Setup 2 has the following characteristics:

(1) It operates according to the DCMD principle, i.e. counter-current flow of warm feed solution and cold distillate.
(2) The flow cell has effective membrane area of 60 cm^2.
(3) It can be used to test different types of membranes and spacers.

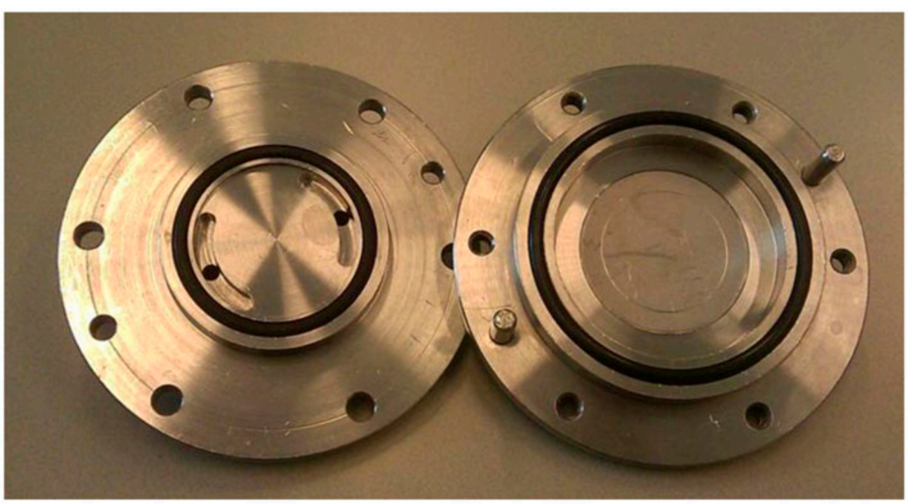

Fig. 3. Setup 1: dead-end test cell (left: feedstock chamber, right: distillate chamber).

Fig. 4. Side view of Setup 1 (upper: feed chamber, lower: distillate chamber).

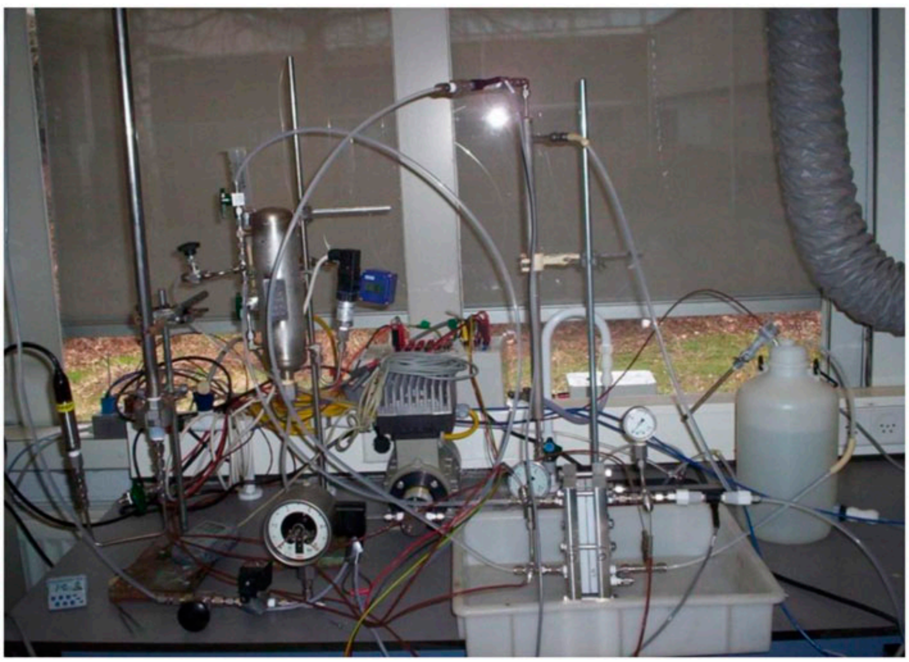

Fig. 5. Setup 2 for MemPower with P_{max} = 10 bar.

(4) The LP (low pressure) feed loop (right side in Fig. 5) contains the feed tank, a low-pressure circulation pump (P_{max} = 0.8 bar), a SS316 plate heat exchanger coupled with a warm thermostatic water bath, a flow meter, a temperature, and a pressure sensor.

(5) The HP (high pressure) distillate loop contains a high-pressure resistant positive flow circulation pump, a single-tube cooler coupled with a cold thermostatic water bath, a pressurized vessel with overflow (for the produced distillate), and a de-aeration valve, temperature and pressure sensors, and a discharge valve controlled by a safety pressure sensor.

(6) The produced distillate is measured via hand metering, and a vertical tube coupled with a pressure sensor (left).

(7) During comparison measurements using various membranes, the temperatures of both water baths were set at 10°C (HP distillate side) and 60°C (LP feed side). This typically resulted in a temperature entering the test cell at the feed side of 57°C, decreasing to ~45°C; and on the distillate side of 30°C, increasing to ~47°C.

4.3. *Setup 3: DCMD*, P_{max} = 22 bar

Fig. 6 shows Setup 3, which is an adaptation of Setup 2 to allow pressures above 10 bar. The changes compared to Setup 2 are:

(1) The HP distillate loop consist of SS316 tubing instead of PE tubing.

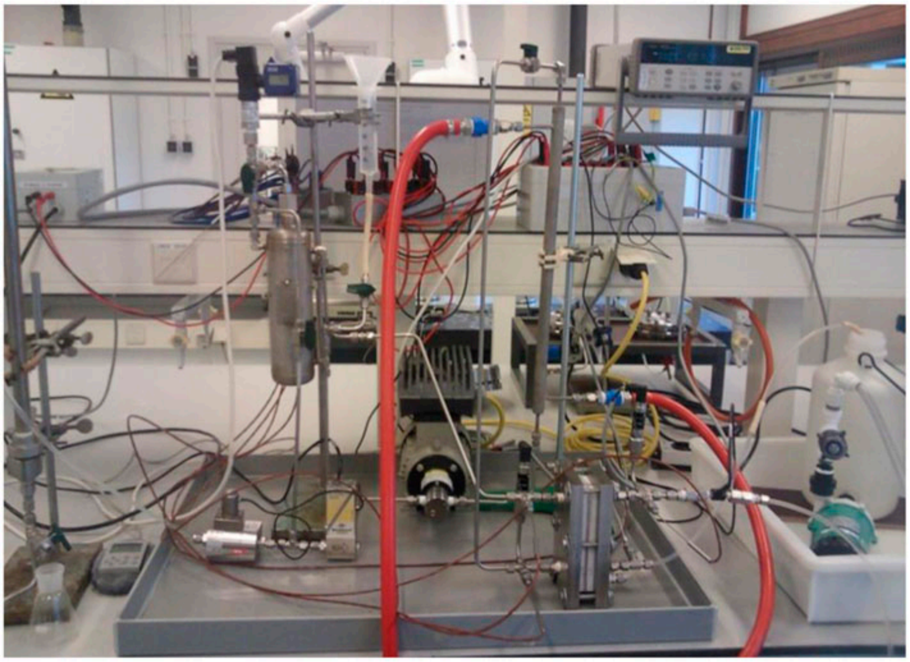

Fig. 6. Setup 3 for MemPower with P_{max} > 20 bar.

(2) The HP discharge valve is changed to a very accurate pressure meter and a flow controller. This enables the discharge of a small flow of distillate at a set pressure without an abrupt change of this pressure.
(3) During comparison measurements using various membranes, the temperatures of both water baths were set at 10˚C (HP distillate side) and 60˚C (LP feed side). This typically resulted in a temperature entering the test cell at the feed side of 57˚C, decreasing to ~45˚C; and on the distillate side of 30˚C, increasing to ~47˚C.
(4) Besides this, the temperature of the LP side was sometimes increased (to a maximum of 90˚C). This allows operation at higher values of the driving force to create higher fluxes and consequently higher power densities.

5. Experimental results

This section describes the results obtained with the three experimental setups discussed in Section 4. The major focus is on the distillate fluxes of the various tested membranes tested at increasing distillate pressure, and the calculated *PD* (see Eq. (1)).

5.1. First proof of principle test with dead-end test cell (*Setup 1*, P_{max} = 6 bar)

The result of the first test is reported in Fig. 7. This figure shows that:

- A stable flux is realized at increasing hydraulic (counter) pressure.
- The *PD*, defined as hydraulic pressure × water flux, equals $2.5\ 10^5 \times 10/(1{,}000 \times 3{,}600) = 0.8$ (W m^{-2}).

5.2. Proof of principle with DCMD test cell (*Setup 2*, P_{max} = 10 bar)

First, the performance of Setup 2 was evaluated using the same membrane as in Setup 1, see Fig. 8. During the first hour of this experiment, the flux was measured at a pressure below 1.5 bar. Next, the pressure was increased up to 5.8 bar. The second to fourth runs (73 → 122 h) were performed at pressures of 3 and 4 bar, respectively. During these tests, the flux seemed to maintain at its (relatively low) level. After this, a decrease in flux was observed. This phenomenon was partly reversible after decreasing the pressure (around 220 h). The flux decreased again after raising the pressure.

These results can be explained by compaction of this membrane at elevated pressure. Measurement of

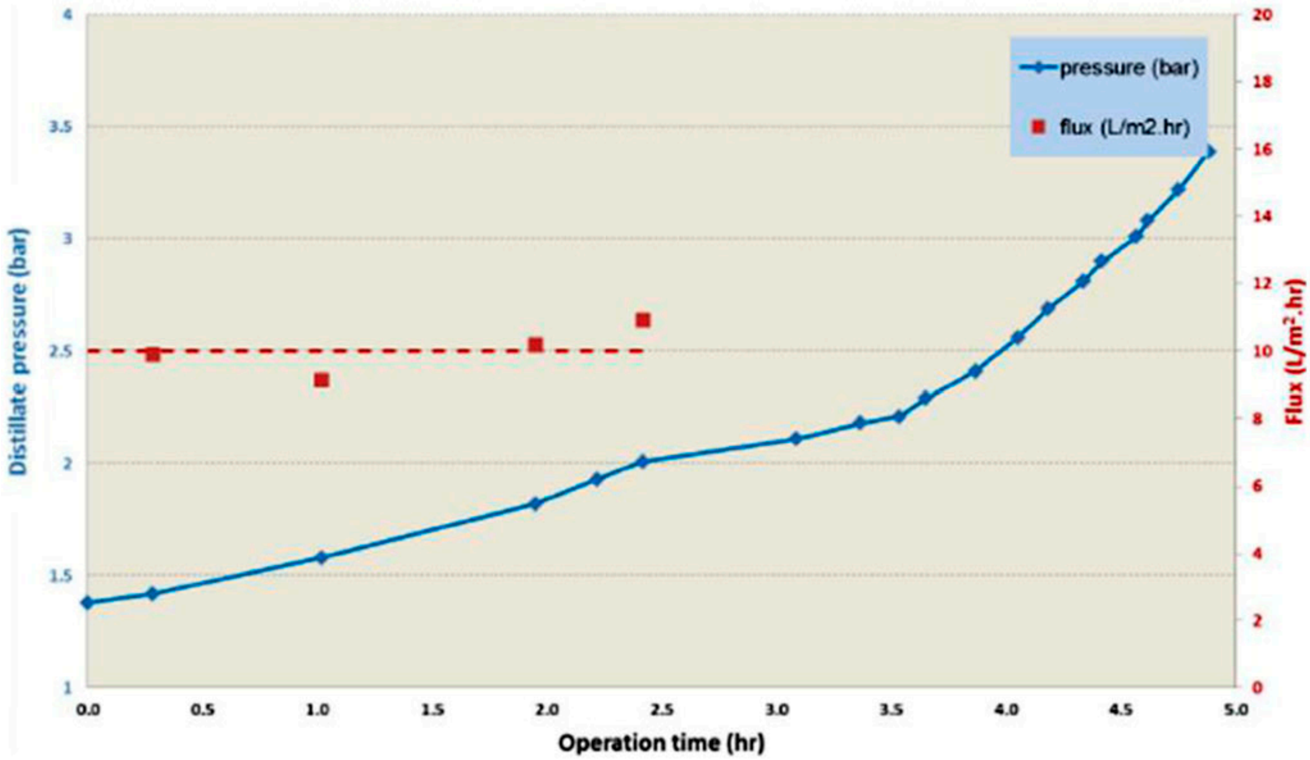

Fig. 7. First MemPower experiment, proving the existence of a positive distillate flux at a negative hydraulic pressure difference across a membrane.

the conductivities of the distillate and feed showed no evidence of wetting (pore leakage) of the membrane. In experiment 2, both the flux and the compaction of this membrane could be considerably improved using a finer support structure (see Fig. 9). However, also here severe compaction of the membrane did occur at a pressure of 5.5 bar; first reversible (at 75 h), later also slightly irreversible (130 h).

The maximum obtained *PD* was relatively low: 0.2 W m^{-2} (at 48 h, p = 3 bar).

5.3. *Proof of principle with adapted DCMD test cell* (*Setup 3*, P_{max} > 20 bar)

After improving the test setup to allow higher pressures, various other types of membranes were evaluated. An overview of the results is shown in Fig. 10. Note that the value of the flux equals the slope of the graphs.

Membrane A shows no compaction (constant flux and linear increasing *PD* at increasing pressure) for pressures up to 13 bar. However, at higher pressures compaction takes place. At a pressure above 20 bar this becomes severe, until at 24 bar the flux becomes zero. Interestingly, even at this pressure no pore wetting occurred, pointing at a fairly narrow pore size distribution, because the breakthrough pressure is determined by the largest pore.

Following the promising results with membrane A, another membrane (D) of the same manufacturer was evaluated, having a smaller pore size and therefore a higher *LEP*, as well as a higher porosity. Although this membrane indeed has a much larger distillate flux, it also shows more severe compaction. The measured maximum *PD* of 0.89 W m^{-2} (at 12 bar distillate pressure) was the highest value obtained at these conditions (T = 60°C; p > 10 bar).

The membranes C–E were also tested at elevated temperatures to allow operation at higher fluxes. Fig. 10 shows the results on *PD*. The highest measured value of *PD* was 3.35 W m^{-2}. This could be already achieved for membrane C at a relatively low pressure of only 2.3 bar pressure. Membrane E shows a lower flux than membrane C. Because of its smaller pore size, its P_{max} is higher. However, this does not result in a higher *PD* at similar temperature, due to this lower flux.

The results also indicate that with hydrophobic, non-compacting, small-pore (and still high surface

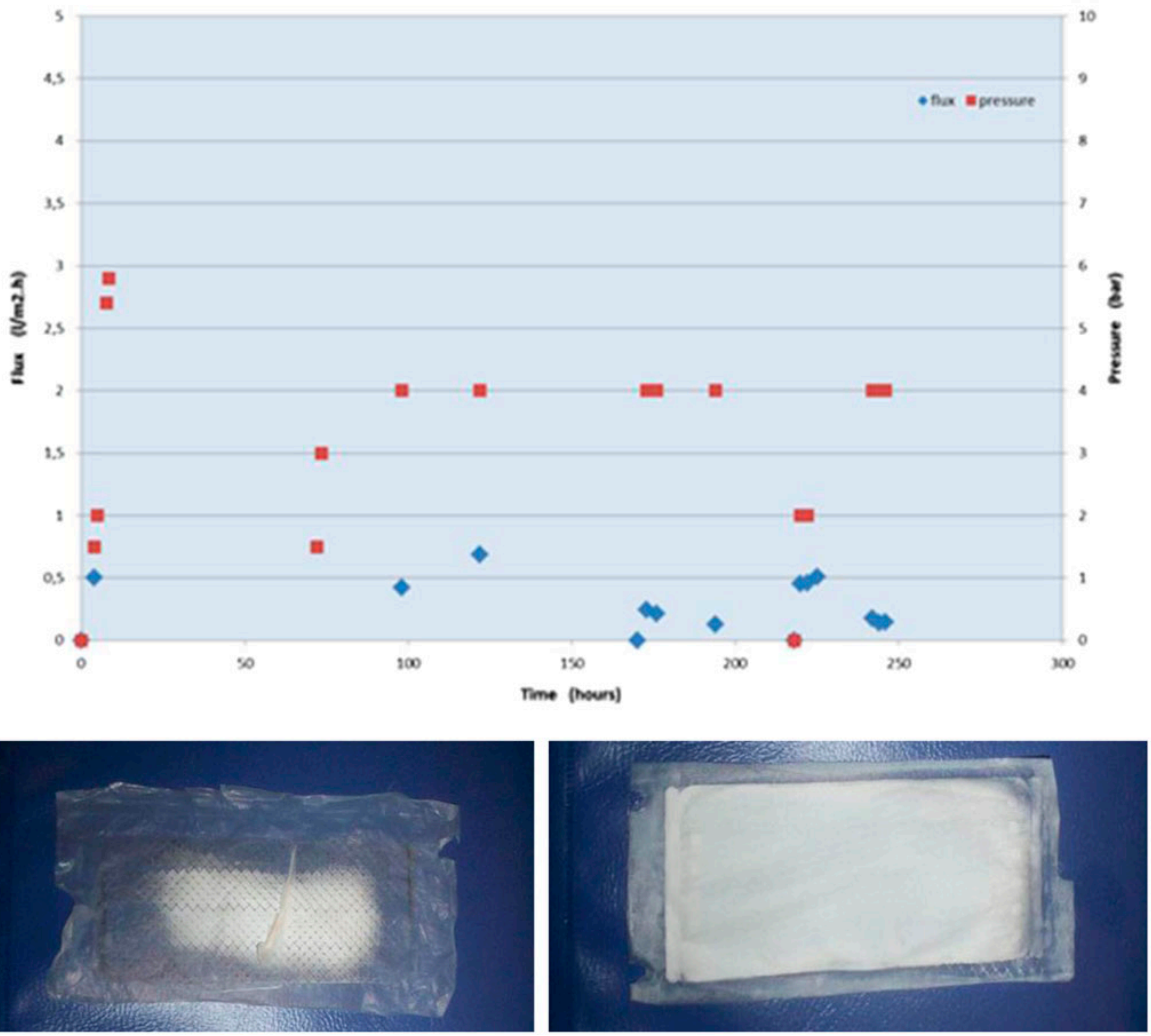

Fig. 8. Flux and hydraulic pressure vs. test time (NB: not continuous) during the first experiment in DCMD Setup 2. The photographs show the tested membranes after experiment 1 (left) and experiment 2 (right).

porosity) membranes it is possible to obtain higher power densities, as forecasted in Fig. 2.

6. Potential business cases for MemPower integrated Memstill®

Various potential business cases have been identified by applying MemPower in TNO's Memstill® technology, see Figs. 1 and 11. Three cases are analyzed in more detail below:

- MemPower for Aqua-Concentrated Solar Power (CSP) Plants.
- CHP-MemPower units for cogeneration of power, heat, and water.
- MemPower for standalone MD (solar driven water production units).

6.1. *Aqua–CSP plants (combined CSP + seawater desalination)*

The integrated MemPower-Memstill® technology can be applied in the steam cycle of a CSP Plant, where the heat of condensation, as released in the condenser, is used to drive a drinking water producing desalination module.

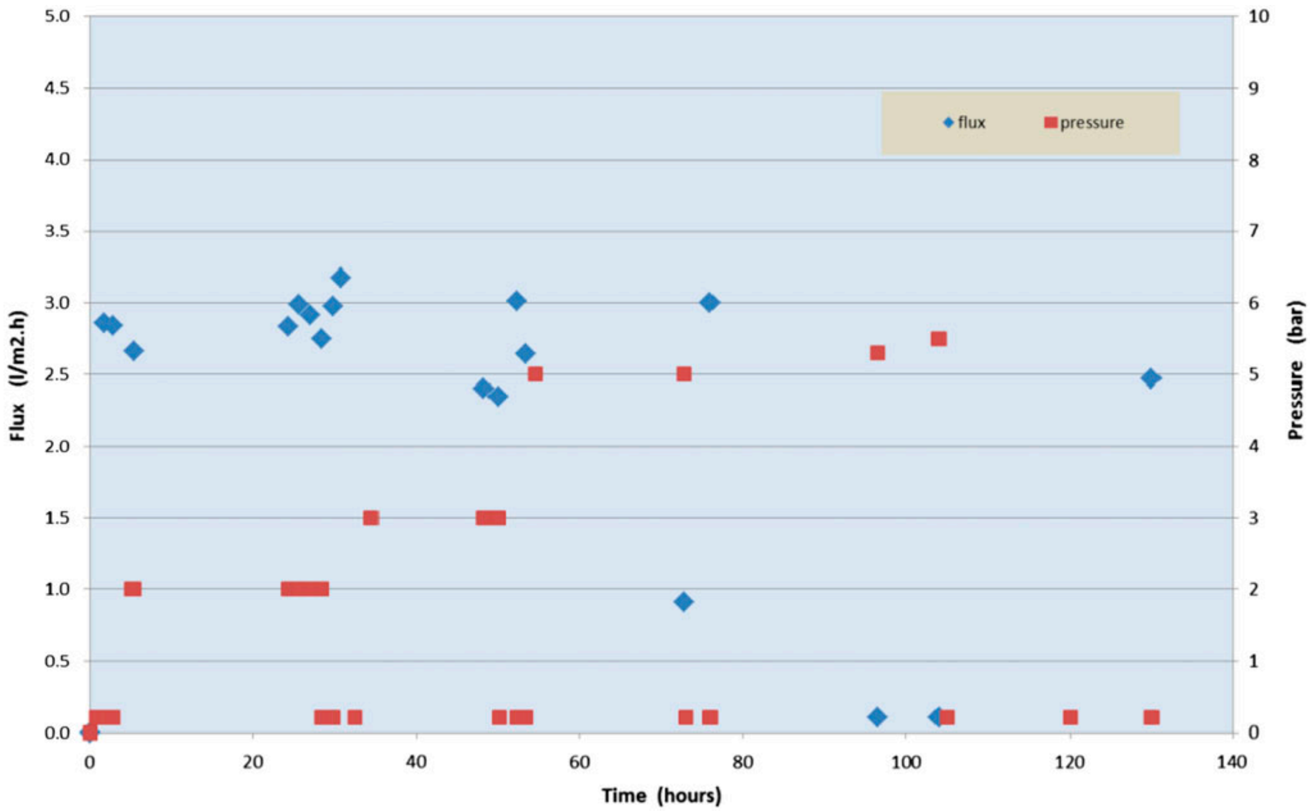

Fig. 9. Flux and hydraulic pressure vs. test time (NB: not continuous) during the second experiment in DCMD Setup 2. A fine spacer (RO permeate spacer) was used as membrane support at the LP side. Figure 8 (bottom) shows the membrane after the test run.

The potential benefits are:

- MemPower increases the output of water and/or electricity at decreased costs relative to reverse osmosis (RO), multiple effect distillation (MED), and MD. This is due to a relatively high reduction in the size of the power plant and the solar field for MemPower because of a significant decrease in parasitic power consumption.
- Extra power is produced compared to RO and MED/MD.
- The water yield is much larger than for MED and RO, and comparable to MD.
- Increased added value can be achieved by increasing the condenser temperature. This is due to lower costs (smaller dimensions) of the steam cycle/power block at increasing condenser temperatures.

6.2. CHP-MemPower units for cogeneration of power, heat, and water

The Combined Heat and Power case is technically very similar to the CSP case. In recent years, many CHP plants are installed for the combined production of heat and power. Especially, in horticulture, these systems are widely used at the moment.

A CHP plant produces electricity (power) at a slightly lower yield compared with large-scale power plants; but has no power transport losses, and co-produces a large amount of heat at a temperature of typically 90˚C. This heat is usually a stream of hot water, and is typically used in horticulture for heating the greenhouses or filling a heat buffer, after which it is recirculated to the CHP unit at a temperature around 50˚C.

This heat of 90˚C could also be an ideal heat source for driving a MemPower unit, producing distilled water and some surplus power. MemPower would then typically skim the top of this heat source, cooling it down to 80˚C. In many cases, this is still very useable for the mentioned heating purposes.

6.3. MemPower for standalone water production units

Integration of MemPower in Memstill®, potentially allows the production of drinking water in small-scale

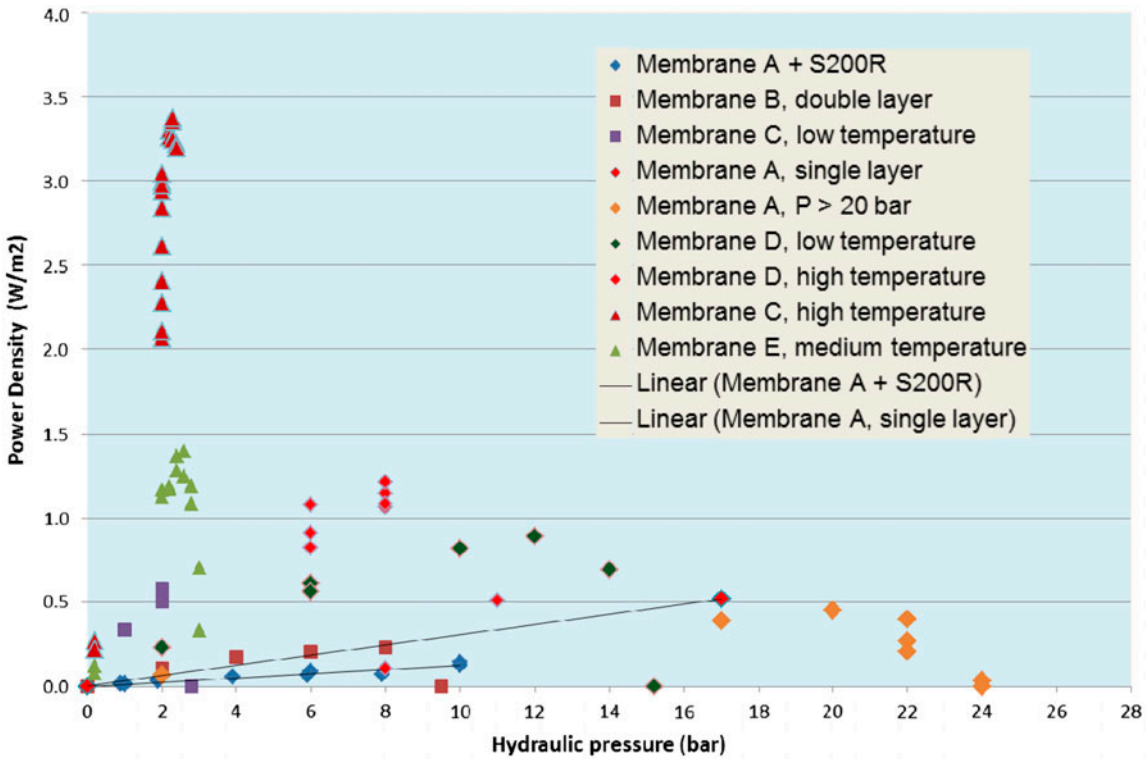

Fig. 10. Overview of the measured power densities for various commercially available membranes, vs. the distillate pressure.

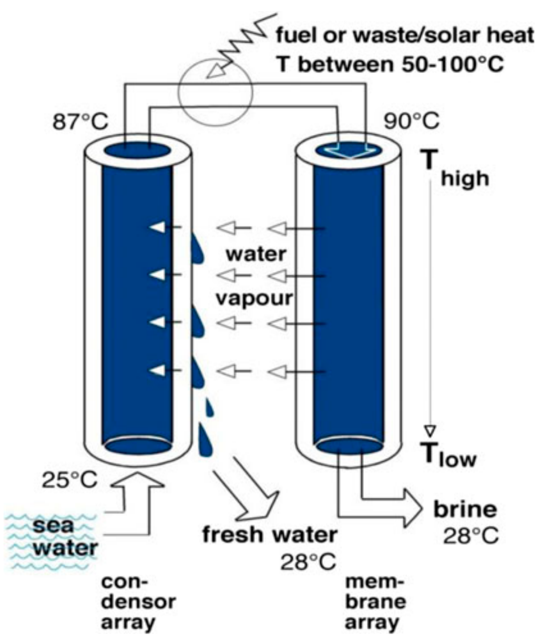

Fig. 11. Principle of Memstill® process as applied on desalination of seawater.

modular standalone solar-driven water production units (10 L d^{-1}).

The potential benefits are:

- The produced power exceeds the electricity consumption of the feed pump which is needed to overcome the pressure drop in such a personal water production system.
- Water production costs of all (benchmark) solar-driven systems are relatively high due to hardware costs, and should be compared with the price of mineral water (200–500 € m^{-3}) rather than with large-scale seawater desalination plants.
- For desalination of seawater, MemPower appears to be cheaper than Memstill® PV, because of the savings of a PV-panel. In addition, RO-PV is even more expensive than both solar technologies due to the higher hardware costs.

It must be noted that for small-scale modular stand-alone water production units in rural areas, less-saline aqueous feedstocks will be used instead of seawater. For these conditions, the advantages of MemPower (MD) become less relative to RO. This is due to the relative low pressures (low electricity consumption) which are needed for the latter case.

7. Conclusions

The proof of principle of MemPower for simultaneous production of clean water and power from waste heat and aqueous feedstocks has been shown:

(1) Water vapor is able to flow against an hydraulic pressure gradient (experimentally proven, but not limited, up to 20 bar) during MD as driven by a temperature gradient.

(2) A pressurized distillate can be obtained utilizing this MemPower principle. It is, therefore, possible to create mechanical power during MD, with a *PD* which almost linearly increases with the distillate pressure.

   (a) Membrane D has shown this linear increase up to 17 bar, but at relatively low fluxes.
   (b) All other membranes showed compaction and/or pore wetting at lower pressures.
   (c) For membrane C, a *PD* of 3.35 $W\,m^{-2}$ was measured at only 2.3 bar.

(3) In principle, the maximum power produced is more than sufficient to drive the pumps in MD, i.e. to develop stand-alone MD (Memstill®) installations. These could be fully driven by thermal energy without consumption of electricity.

(4) Potentially, much higher power densities can be achieved. However, this requires the development of new hydrophobic pressure-resistant (non-compacting) membranes which combine a high permeability with a high *LEP*.

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