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Solar thermal-driven desalination plants based on membrane distillation

Joachim Koschikowski*, Marcel Wieghaus, Matthias Rommel
Fraunhofer-Institut für Solare Energiesysteme (ISE), Heidenhofstrasse 2, D-79110 Freiburg, Germany
Tel. +49 (761) 4588-5294; Fax +49 (761) 4588-9000; email joako@ise.fhg.de

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Abstract

In arid and semi-arid regions the lack of drinkable water often corresponds with high solar insolation. These conditions are favourable for the use of solar energy as the driving force for water treatment systems. Especially in remote rural areas with low infrastructure and without connection to a grid, small-scale, stand-alone operating systems for the desalination of brackish water from wells or salt water from the sea are desirable to provide settlements with clean potable water. Fraunhofer ISE is currently developing a solar thermally driven stand-alone desalination system. The aim is to develop systems for a capacity ranging from 0.2 to 20 m³/d. Technical simplicity, long maintenance-free operation periods and high-quality potable water output are the very important aims which will enable successful application of the systems. The separation technique on which the system is based is membrane distillation. The implemented heat source is a corrosion-free, seawater-resistant, thermal collector or a standard flat-plate or vacuum tube collector coupled with a corrosion-free heat exchanger. Laboratory tests under defined testing conditions of all components are very important for the preparation of successful field tests under real conditions.

Keywords: Membrane distillation; Water supply; Remote areas; Solar thermal desalination; Maintenance-free operation

1. Introduction

In many places world wide drinkable water is a scarce commodity, whose lack will increase dramatically in the future. Today, seawater desalination plants are well developed on an industrial scale. Each day about 25 Mm³ of world water demand is produced in desalination plants. These “water factories” have a capacity ranging up to 230,000 m³/d and can provide large cities with drinkable water.

*Corresponding author.

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Small villages or settlements in rural remote areas without infrastructure do not profit from these techniques. The large plants use a complex technology and cannot easily be scaled down to very small systems and water demands. Furthermore, the lack of energy sources as well as a missing connection to the grid complicate the use of standard desalination techniques in these places.

The fact that the lack of drinkable water in arid and semi-arid regions often corresponds with high solar insolation speaks for the use of solar energy as the driving force for water treatment systems. These systems must be adapted to the special conditions required by solar energy powering, low water demand, challenging ambient conditions and the lack of well trained technicians for set-up and maintenance. Thus, the systems to be developed must be able to operate in a stand-alone mode; they must be maintenance free, robust and modular in order to resize them to a wide range of user profiles. They must be able to withstand different raw water compositions without chemical pre-treatment in order to develop standardised stand-alone systems for all current types of sea and brackish water.

Mainly, two different options are given for using solar energy for desalination: photo voltaic (PV)-coupled revere osmosis (RO) systems and solar thermally driven distillation systems. While grid-coupled RO systems are well developed, it is known that difficulties exist in operating small-scale, PV-driven, stand-alone systems. The comparison between solar thermally driven evapoation systems and PV-driven RO systems with respect to long-term system efficiency, reliability and appropriateness cannot finally be assessed.

The most common of thermally driven stand-alone desalination systems is the solar still type. Its construction is quite simple, but due to the fact that its thermal efficiency is very low, the specific collector area per cubic meter of desalted water is very high. Experience with simple solar stills was negative, especially with respect to low system efficiency [1]. In advanced solar thermally driven desalination systems, the desalination unit must be separated from the solar heat generator in order to achieve the necessary improvement of the total desalination system efficiency.

This paper reports on the on-going development of solar thermally driven stand-alone desalination systems for a capacity ranging from 0.2 to 20 m^3/d. The aim is to develop systems which are completely powered by solar energy, which are technically simple and robust, that allow for long maintenance-free operation periods and that produce high-quality potable water. Another important factor for the marketability of the system is the reduction of the investment and maintenance costs. To achieve these aims, separated desalination units based on the membrane distillation technique (MD) with internal or external heat recovery function are coupled with highly effective solar thermal collectors. The implemented heat source for very small capacities is a corrosion-free, seawater-resistant thermal collector developed by Fraunhofer ISE in 1999. Thus, system costs can be reduced since the expensive heat exchanger and pump, including PV supply and control unit for the collector loop, can be saved. For larger systems a design based on a sepa-rated collector loop coupled to the brine loop by a seawater-resistant heat exchanger may be the better option since cheaper standard flat-plate collectors or vacuum tube collectors can be used.

2. Membrane distillation (MD)

The MD technique holds important advantages with regard to the implementation of solar-driven stand-alone operating desalination systems. The most important advantages are:

- The operating temperature of the MD process is in the range of 60 to 80°C. This is a temperature level at which thermal solar collectors perform well.

- The membranes used in MD are tested against fouling and scaling.
- Chemical feed water pre-treatment is not necessary.
- Intermittent operation of the module is possible. Contrary to RO, there is no danger of membrane damage if the membrane falls dry.
- System efficiency and high product water quality are almost independent from the salinity of the feed water.

The principle of MD [2–4] is briefly described below.

Contrary to membranes for RO, which have a pore diameter in the range of 0.1 to 3.5 nm, membranes for MD have a pore diameter of about 0.2 μm. The separation effect of these membranes is based on the fact that the polymer material it is made from is hydrophobic. This means that up to a certain limiting pressure the membrane cannot be wetted by liquid water. Molecular water in the form of steam can pass through the membrane. In Fig. 1 the principle of MD is depicted.

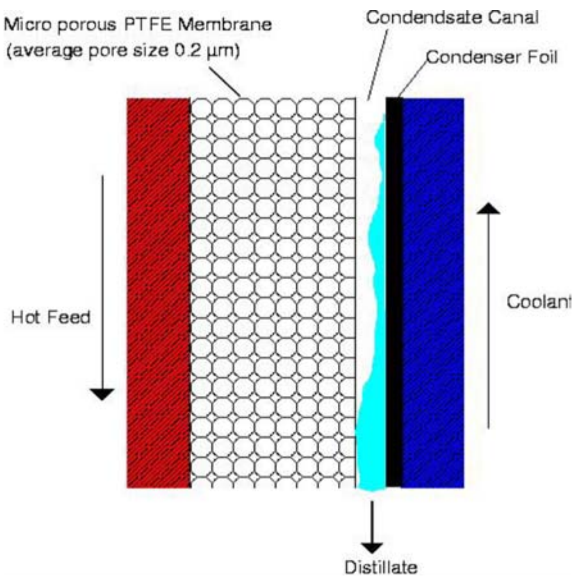

Fig. 1. Principle of membrane distillation.

On the one side of the membrane, there is seawater, at a temperature, for example, of 80°C. If at the other side of the membrane there is a lower temperature, for example, by cooling the condenser foil to 75°C, then there exists a water vapour partial pressure difference between the two sides of the membrane, and thus water evaporates through the membrane. The water vapour condenses on the low-temperature side and distillate is formed.

For the design of a solar-powered desalination system, the question of energy efficiency is very important since the investment costs mainly depend on the area of solar collectors to be installed. Also the power consumption of the auxiliary equipment (for example, the pump) which will be supplied by PV has an important influence on total system costs.

Therefore, the system design to be developed has to focus on a very good heat recovery function to minimise the need of thermal energy. Heat recovery can be carried out by an external heat exchanger or by an internal heat recovery function were the feed water is directly used as coolant for the condenser channel.

The principle of the internal set-up of the MD module with internal heat recovery function is shown in Fig. 2. All together, there are three different channels: the condenser, evaporator and distillate. The condenser and the distillate channels are separated by a impermeable condenser foil, while the evaporator and the distillate channel are separated by a hydrophobic, steam permeable membrane. The hot water (e.g., 80°C inlet temperature) is directed along this membrane, passing the evaporator channel from its inlet to its outlet while cooling down (e.g., 30°C evaporator outlet temperature). The feed water (e.g., 25°C inlet temperature) passes through the condenser channel in counter flow from its inlet to its outlet while warming up (e.g., 75°C outlet temperature). The partial pressure difference caused by the temperature difference on both sides of the membrane is the driving force for the

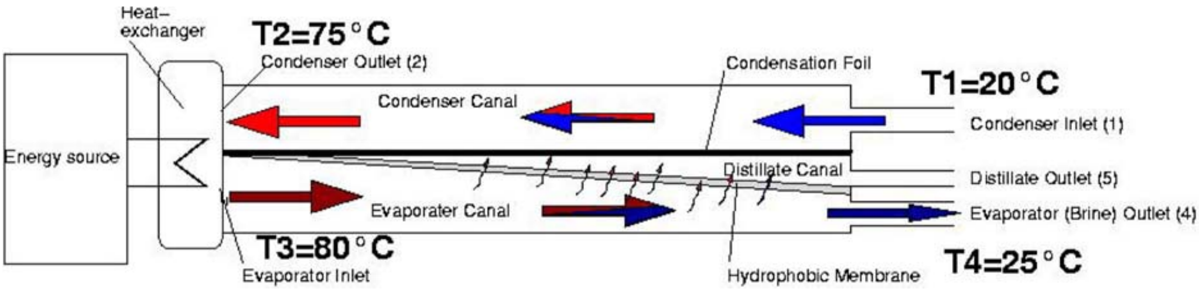

Fig. 2. Principle set-up of the MD-module with an integrated heat recovery system.

steam passing through the membrane. The heat of evaporation is transferred to the feed water by condensation along the condenser foil. Thus the heat of evaporation is (partly) recovered for the process. Because the energy for evaporation is removed from the brine, the brine temperature decreases. The liquid distillate is gained from the distillate outlet on a temperature level between the feed in- and brine- outlet. The input heat necessary to achieve the required temperature gradient between the two channels (e.g., 5°C) is introduced into the system between the condenser outlet and the evaporator inlet. Thus thermal energy consumption of the system is given by the volume flow rate and the temperature lift of the feed water between these two points. The heat recovery function has an important influence on the energy consumption of the system. In thermal desalination processes the gained output ratio (GOR) is an important parameter for the evaluation and assessment of such systems.

The GOR can be calculated as the quotient of the latent heat needed for evaporation of the water produced and the input energy supplied to the system:

$$GOR = \frac{\Delta h_{\text{evap}} \dot{m}_{\text{distillate}}}{\dot{Q}_{\text{input}}}$$

Moreover, it is necessary to take into account that only a part of the recovered energy is latent heat from the condensing process. The other part is sensible heat transferred by heat conduction across the membrane and the distillate channel. This part has a negative influence on the efficiency of the process because it decreases the temperature gradient between evaporator and condenser without any effect on the material transport through the membrane.

The factor that gives a relationship between the latent heat and the total amount of recovered energy is the thermal efficiency factor η_{th} of the membrane distillation module, calculated as:

$$\eta_{\text{th}} = \frac{\Delta h_{\text{evap}} \dot{m}_{\text{distillate}}}{\dot{m}_{\text{feed}} c_p \left(T_{\text{condenser outlet}} - T_{\text{condenser inlet}}\right)}$$

Using this expression for the efficiency factor, another expression for the GOR can be given by which the GOR can be calculated from the module inlet and outlet temperatures:

$$GOR = \eta_{\text{th}} \frac{T_{\text{condenser outlet}} - T_{\text{condenser inlet}}}{T_{\text{evaporator inlet}} - T_{\text{evaporator outlet}}}$$

One design for a module is the formation of the necessary flow channels by spiral winding of membrane and condenser foils to form a spiral-wound module. A sketch and a photo of the channel assembly of the module are shown in cross section in Fig. 3.

The technical specifications of the MD module that we are using for the current investigations are:

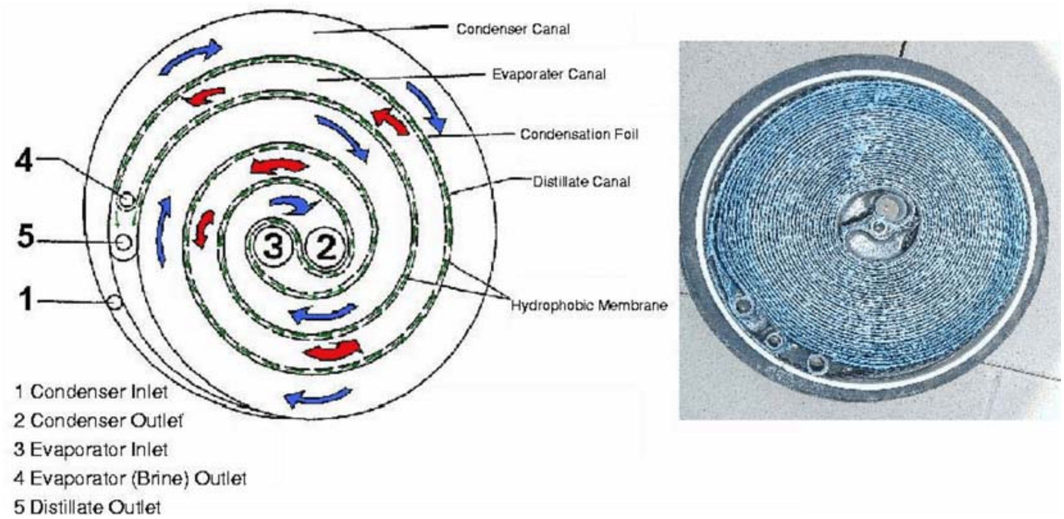

Fig. 3. Channel assembly of the spiral-wound membrane distillation module.

- hydrophobic PTFE membrane, mean pore size 0.2 μm
- height 700 mm
- diameter 460 mm
- membrane area 8 m²
- feed temperature at evaporator inlet 60–85°C
- specific thermal energy consumption 140–200 $kWh/m^3_{distillate}$ (GOR about 4–6)
- distillate output 20–30 l/h
- all parts are made of polymer materials (PP, PTFE, synthetic resin)

3. Development of robust and simple systems

Our current work focuses on the development of stand-alone MD test systems for capacities ranging between 150 an 2000 l/d. For reliable systems all components are important. The operating conditions concerning the handling of hot seawater and strong ambient conditions as expected in many potential installation locations are quite difficult. Therefore, special stress tests must be carried out on each component of the system in the laboratory before field tests of systems can be conducted successfully. Measurements of the thermodynamic efficiency and behaviour of the MD module lead to the characteristic parameters used for system simulation calculations and system design. Three different test stands were set up at our institute.

3.1. Seawater test facility

Resistance against hot seawater is not given for most metallic materials. The special conditions caused by the intermittent operation of solar-powered systems thus complicate the choices of materials. For example, CuNi10Fe is used in many desalination plants and withstands hot seawater but needs a steady flow rate, or else pitting corrosion can occur and destroy components in a short time. Polymer materials also have to be tested. To give an example here, the maximum temperature to which standard polymer materials (PP, PE, PVC) can be used is in the same range in which the MD module is operated, but the stagnation temperature of the solar collector field is much higher.

All components in the fluid cycle of the desalination system (i.e., pumps, valves, degasser, heat exchangers, tubes and fittings) must be tested in long-term tests and accelerated ageing tests with seawater. The test facility consists of a fluid cycle with test lines for components made from different materials. MD modules can also be integrated and operated in the loop. Thus, long-term desalination performance can be tested by measuring the salinity of the distillate.

Computer-controlled heater and pump switches allow the simulation of intermittent operation cycles as expected for future outdoor systems or stress tests with short cycled changes of temperature and volume flow.

3.2. Pump test facility

The fact that the desalination systems will be operated as stand-alone systems requires a PV system as the supply for electrical auxiliary equipment. Most of the electrical power is consumed by the pump. Thus, the efficiency of the pump is an important influence on the design layout of the PV area and therefore on the investment costs of the total system. The pressure drop of the MD module and all other components in the loop should be as low as possible to minimise the pump energy.

A test facility was set up to carry out investigations on different pump types concerning their specific energy consumption, their starting characteristics and their coupling to PV. Different pumps, auxiliary parts or the MD module can be integrated into the circuit. The pressure drop, temperature and volume flow can be measured as well as the electrical power consumption of the pump. The pump can be connected to a PV module, and during outdoor tests current and voltage of the PV-module can be monitored.

3.3. Performance test facility

Two important tasks of the work to be carried out are the system design for complete test systems by simulation calculations and the development of new spiral-wound MD modules. To carry out system simulation calculations, an empirical simulation model of the MD module must be developed, which is based on measured performance data. Exact performance measurements must be feasible to determine improvements concerning new module constructions. The dynamical behaviour of the MD module is a very important question for the system design with respect to intermittent operation of a solar collectors as a heat source.

A test facility was set up that allows the determination of the module's GOR and η thermal value for different inlet temperatures and different feed volume flows. Also the dynamic start-up and cool-down behaviour can be monitored.

3.4. Performance results

The parameters GOR and η_{th} were determined depending on the feed volume flow and the evaporator inlet temperature. The measured parameters are the distillate volume flow, the feed volume flow, the condenser in- and outlet temperature and the evaporator in- and outlet temperature. The additional heat supplied into the system from outside can be calculated from the temperature difference between the condenser outlet and the evaporator inlet, the feed volume flow and the specific heat capacity, c_p, of the feed. The heat demand for different feed flow rates between 200 and 400 l/h depending on the evaporator inlet temperature is shown in the right diagram of Fig. 4. The diagram on the left site shows the corresponding distillate volume flow. As described above, the GOR value can be calculated by dividing the product of distillate output and the specific enthalpy of evaporation ($\dot{m}_{distillate} \times r$) by the heat input ($\dot{Q}_{in}$). For example, the calculated GOR for a volume flow of 350 l/h at an evaporator inlet temperature of 75°C ($r_{70°C}$= 2321.5 kJ/kg) is 5.5. The specific energy consumption per cubic meter distillate for these operation conditions is in the range of 117 kWh/ m³.

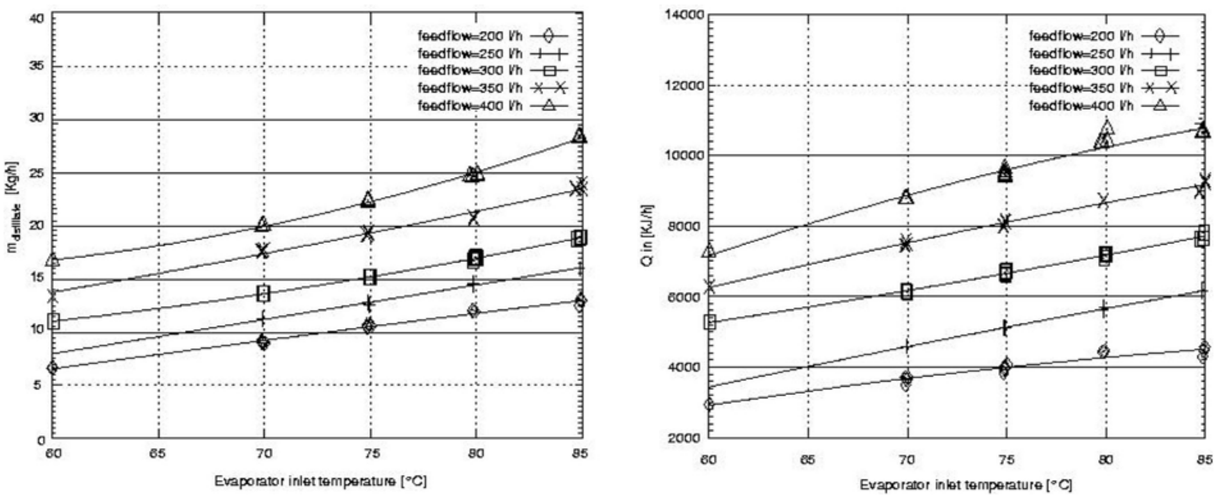

Fig. 4. Distillate output and heat supply of a MD module with a 7 m² membrane area measured under laboratory conditions. Left: Distillate mass flow depending on the evaporator inlet temperature for different feed volume flows. Right: Total energy consumption depending on the evaporator inlet temperature for different feed volume flows.

3.5. Dynamic behaviour of the MD module

The need for heat storage depends on the response time of distillate output referring to changes at the evaporator inlet temperature. Measurements carried out, as given in Fig. 5, show that the response of distillate output (m_{dest}) follows the temperature rise at the evaporator inlet ($T_{evap\text{-}in}$) very closely between 0:00 and 0:30 h. At about 0:30 h the heat input was interrupted and the module was operated in by-pass mode ($T_{condenser\ outlet} = T_{evaporator\ inlet}$). It can be seen that after 30 min distillate is still produced even when there is no more heat supplied into the system. The conclusion can be drawn that an intermittent operation with a solar collector under varying solar radiation conditions is possible without the use of a thermal storage.

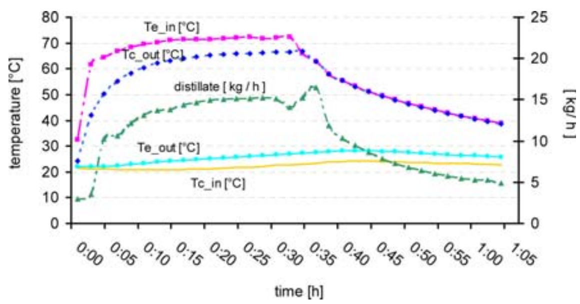

Fig. 5. Investigations on the dynamic behaviour of the MD module.

3.6. Small-scale test system

A compact experimental desalination system as sketched in Fig. 6 consisting of the MD module, a corrosion-free solar collector, a pump and a temperature hysteresis controller was installed on the outdoor test site of our institute. Sensors for temperatures, volume flow and solar insolation were integrated for the monitoring of the operational parameters. A PV-power supply was not integrated, but all electrical parts were supplied by the grid. Since the energy for the distillation process is almost independent from the salt concentration, the system has been operated with sweet water up to now to avoid trouble with corrosion at auxiliary components.

The results from the experimental investigations showed that the handling of the system is quite easy, and long-term operation periods without maintenance are possible. The performance of the system is shown in Fig. 7 as an example for one day in June 2002. The system begins operation at 10:15 h when the solar insolation is in the range of 700 W/m². The feed flow is manually adjusted to about 225 l/h. The maximum evaporator inlet temperature reaches 90°C. At the same time the maximum of distillate production reaches 15 l/h. The total amount of distillate gained on that day was about 81 l. The maximum of distillate gain during the test period of summer 2002 was about 130 l/d under the meterological conditions at Freiburg in central Europe.

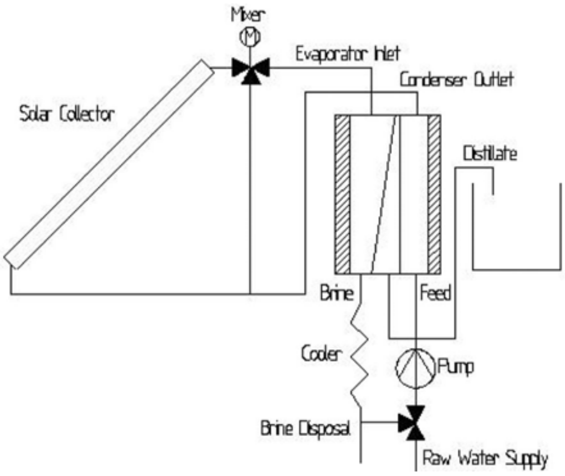

Fig. 6. Test system installed on the roof of the Fraunhofer ISE in Freiburg, Germany.

3.7. System simulations

One-day and annual simulation calculations for three different locations, (Eilat, Israel; Muscat, Oman; and Palma de Majorca, Spain) were carried out. It can be seen from Fig. 8 that, for example, in Eilat a maximum distillate output of 28 l/d and m² collector area (equal to total amount of 161 l/d) can be gained on a day with good weather conditions during the summer. The minimum production rate is in the range of 11 l/d and m^2 collector area (equal to total amount of 63 l/d) in December. Two different control strategies were investigated [5].

Since the most common small-scale solar desalination systems in Third World countries are solar stills, a brief comparison between the simulated performance of a MD system and the performance of a simple solar still [1] is given in

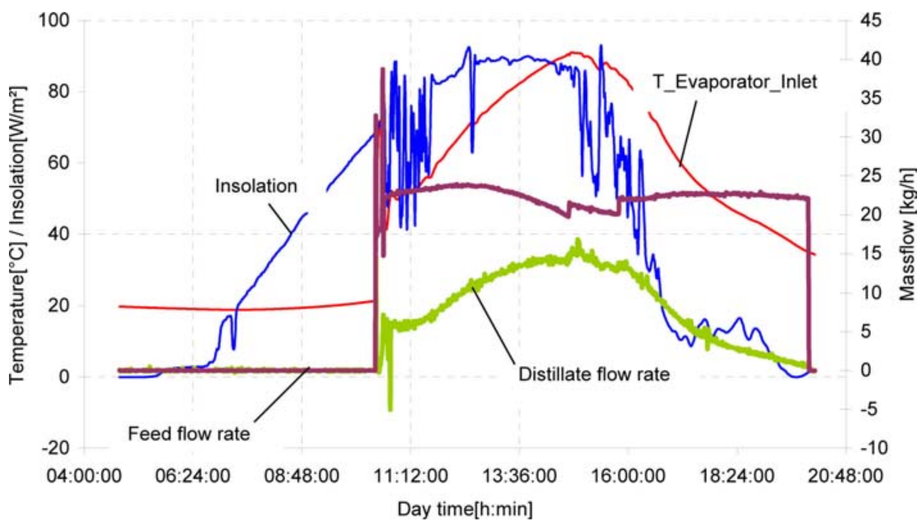

Fig. 7. Measured performance of the test system (5.9 m² collector area) during one day operation in Freiburg, Germany, 04/06/2002.

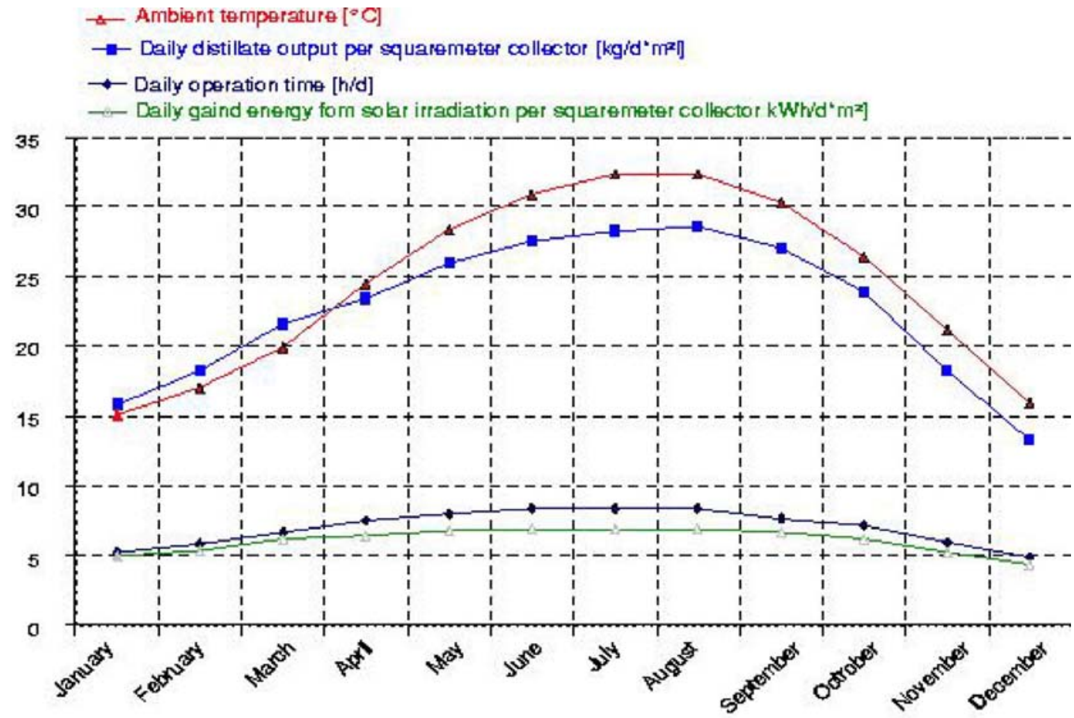

Fig. 8. Simulation calculations with weather data sets from Eilat, Israel, for a 12 m² collector area and a 7 m² membrane MD module.

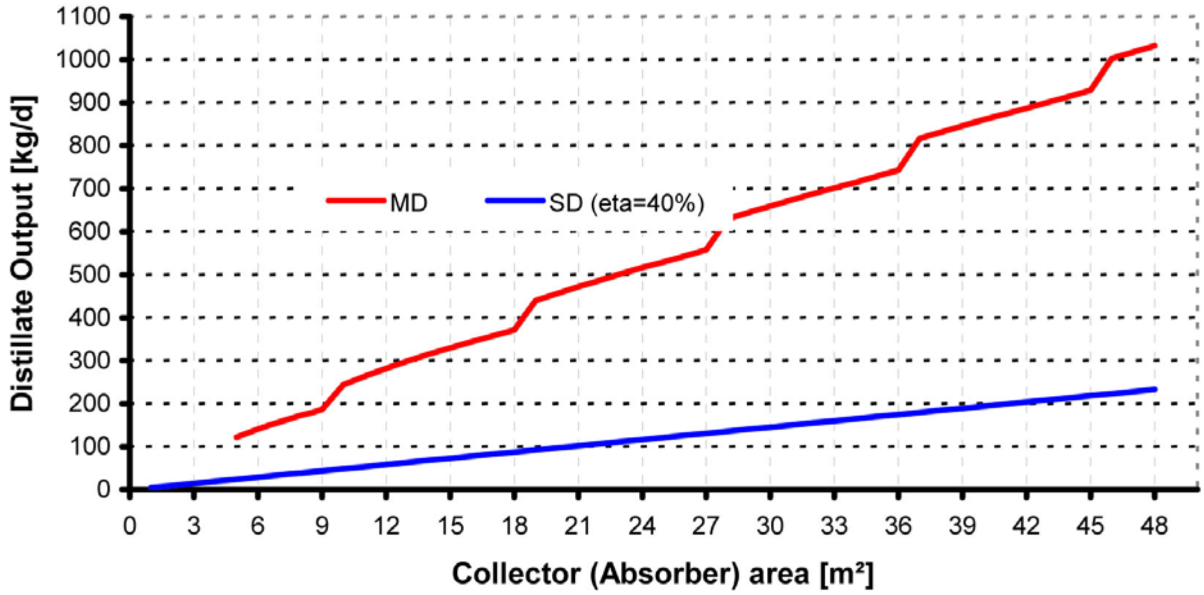

Fig. 9. Comparison between calculated gains of a simple solar still and a MD system. The values are calculated for an insulation of 7,76 kWh/d.

Fig. 9. The used insolation data for the performance calculations were averaged from the weather data sets from Eilat. Since the MD system is modular and each module has a maximum distillate capacity in the range of 150 l/d, the number of modules rise step by step (the graph represents these steps since the system performance rises non-linear when a new module is attached). The comparison shows that the simulated MD system has a 4.5 times higher distillate output.

4. Conclusions

The development of small stand-alone desalination systems is an important task to provide people in rural remote areas with clean potable water. The fact that the lack of drinkable water often corresponds with a high solar insolation speaks for the use of solar energy as the driving force for a water treatment system. Membrane distillation is a process with several advantages regarding the integration into a solar thermally driven desalination system. Simulation calculations for such systems with module characteristics derived from several experimental investigations were carried out for different potential installation locations. The simulation results show that a very simple compact system with a collector area less than 6 m² and without heat storage can distill 120 to 160 l of water during a day in the summer in a southern country.

Experimental investigations on a testing system are currently being carried out at Fraunhofer ISE. New MD modules will be developed aiming at a higher GOR value and a lower pressure drop.

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