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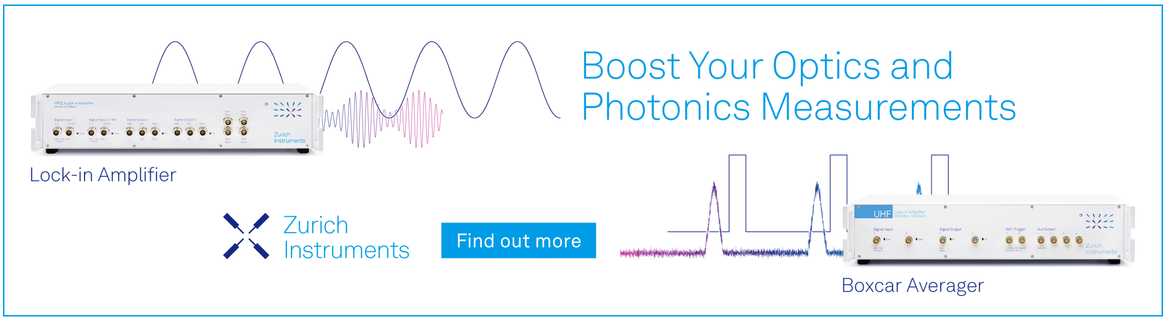

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CPV-T Mirror Dish System Combined with Water Desalination Systems

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Abstract. In this work a combined system consisting of a CPV and thermal (CPV-T) system connected with a reverse osmosis (RO) and membrane distillation (MD) for desalination is presented. In the CPV-T electrical energy is generated. The electrical energy is partly needed to run the desalination systems (e.g. pumps). The surplus electricity can be fed into the grid or an electrical storage system. The reverse osmosis process is the most energy efficient and established way of desalting brackish water and high volumes of pure water can be reached. However, with rising salinity the specific energy consumption (SEC) of RO rises significantly. Therefore, a second desalination system is introduced, the MD. The distillation is driven by the difference in temperature and vapor pressure of two fluid cycles. Hence, in the MD the thermal energy generated in the CPV-T system is used to heat the cycle of the high temperature side. The MD process runs with low temperature heat (<100 °C) and its SEC is less sensitive to the water salinity than the RO-process. Therefore MD is suitable to achieve high brine salinity by further concentrating the brine resulting from the RO-process. The connection in series of the both desalination technologies is especially useful to treat brackish water that is often found in high DNI regions, thus match to the CPV technology very well. The scarce water resources in dry regions are of high value and should therefore be as fully used as possible. In addition, the quantity of brine that needs to be disposed of is reduced when concentrating to a high salinity.

INTRODUCTION

A well-known concentrator photovoltaic (CPV) system design consists of mirror dishes focusing the light onto actively cooled dense array receivers also called compact concentrator modules (CCM) [1, 2]. Mirror optics shows no chromatic aberration and therefore concentration factors of more than 1000x with high optical efficiency can be achieved. The CCM is fully separated from the concentrator optics and must be actively cooled, i.e. this receiver provides in addition to the electrical energy also thermal energy. Therefore, total CPV system efficiencies of more than 70 % have been shown [3, 4]. The thermal energy can be used for domestic or process water heating as well as in additional processes like solar cooling or desalination. Specifically the latter is of interest since the supply of fresh water is a global challenge and especially crucial in dry, sunny climates. Locations with high resources in direct normal irradiance (DNI) are very suitable for the CPV technology. The locations are often inlands and in arid areas. Within these regions typically salty groundwater (brackish water) resources are available which might be used to prepare fresh water. In this paper, we present a CPV mirror dish test setup that is combined with desalination processes. Firstly, a reverse osmosis (RO) system [5] is used to produce fresh water with a very low specific energy demand (SEC). Some of the electricity generated in the CPV system is used to run the RO-system. As brackish water is a valuable resource it is advisable to use the concentrate stream of the RO to gain as much fresh water as the solubility of the salt components allow and to reduce the amount of brine. This is achieved by feeding the concentrated water from the RO in a second cycle of a membrane distillation (MD) process. The MD process needs thermal energy to heat up the feed water. This thermal energy is also delivered by the CPV-T mirror dish system.

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CPV-T AND DESALINATION SYSTEM DESIGN

The complete system has three main technologies, see also Fig. 1. Firstly, the paraboloid mirror dish that concentrates the solar radiation to the CCM which generates the electrical and thermal energy. The second technology is the reverse osmosis RO system which produces the major portion of fresh water and at the same time concentrates the brackish water to higher salinity. The RO-concentrate is collected in a storage tank. As in the RO cycle high pressures are required to overcome the osmotic pressure, electricity is needed to run the pumps. The electricity consumption is reduced by introducing energy recovery systems (indicated in Fig. 1). The RO-concentrate is used as feed fluid for the third technology the membrane distillation system. In the MD the brackish water is concentrated in a batch process further and fresh water is produced (distillate). In the MD system the vapor pressure difference and temperature difference between a condenser and evaporator channel is the driving force for the transport of water vapor through the membrane. At Fraunhofer ISE the air gap membrane distillation system has been developed [6, 7]. To heat up the feed into the evaporator channel, thermal energy from the CPV-T system is used. The thermal energy provided by the cooling cycle of the CPV-T system is transferred to the MD cycle by a heat exchanger in order to protect the CPV receiver from corrosive and possibly contaminated fluid. The CPV-T system supplies electrical energy for control devices and pumping and the thermal energy demand for both desalination systems. Surplus electricity can be fed into the grid or an electrical storage system. A general schematic of the design is shown in Fig. 1.

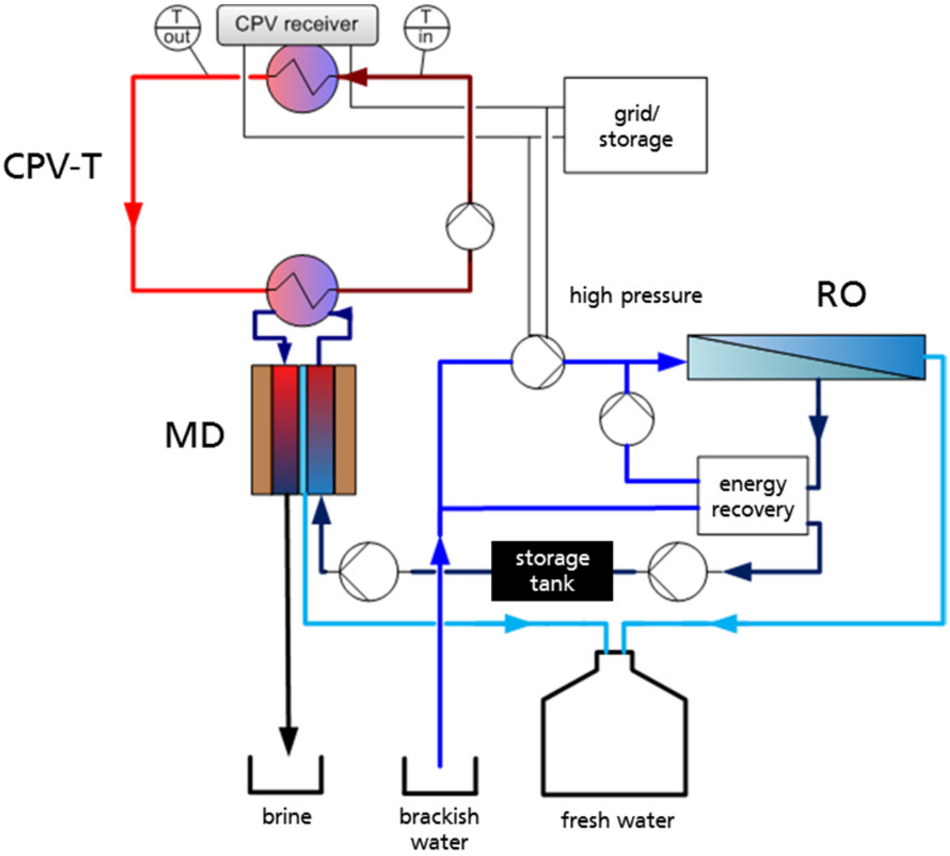


FIGURE 1. Flow chart of the system with CPV-T, membrane distillation (MD) and reverse osmosis (RO). To simplify, the pumps of the MD cycle and low pressure cycle of the RO are not shown.

Specific Design - Example

To design and optimize the complete system a simulation platform was established based on the in-house developed platform ColSim [8]. In this way different operating points and sequences of ambient conditions (irradiation, temperature) were investigated by simulating a full day operation of the CPV-T and desalination systems.

One example for a desalination system configuration is presented in the following. The system design is optimized and adapted further for a specific location, i.e. Keetmanshopp (Namibia). The DNI data were taken from Metonorm 7.0 for a typical day in August. A DNI value of more than 500 W/m² was set as sufficient energy to start the system. This DNI was available for 9:22 hours. The system design parameters are given in Table 1. The thermal energy need of the MD is 200 kWh_{th} per m³ of produced permeate ([7] fig 4.9) which can be achieved due to the internal heat recovery realized in the MD membrane modules. The membrane of the RO is 22 m². For the MD a spiral wound membrane module as described in [6] is assumed with a height of 0.7 m and a length of 63 m. The water flow into the RO is 500 l/h and the flow of the fresh water is 400 l/h. This gives a concentrate flow of 100 l/h which is used as feed flow for the MD.

TABLE 1. Design parameters for the desalination system. The specific energy demand for produced permeate (SEC) is given for very small brackish water RO system and a high concentrating MD.

Technology	Area of the membrane [m²]	Specific energy demand for produced permeate (SEC))	Flow of the feed [l/h]	Flow of the permeate [l/h]
Reverse osmosis (RO)	22	3 kWh_{el}/m^3	500	400
Membrane distillation (MD)	0.7 x 63	200 kWh_{th}/m^3 1.8 kWh_{el}/m^3	100	60

In Table 2 the result of the one day simulation for the desalination systems are listed. In the example the salinity of brackish water with 10 g/kg was increased to 122.5 g/kg. Because of limited solubility of some salts this is only possible in combination with an appropriate pre-treatment e.g. ion-exchange softening or pH adjustment. Details should not be discussed here. The fresh water typically has a salinity of 0.2 g/kg. The MD has a typical recovery ratio (defined as the ratio between product and feed water) of 80 %. This gives a total recovery ratio of 92 %. In the system 4306 liter of pure water are produced whereas only 374 liter of waste water are left. The CPV-T system is designed for 14 $kW_{p,th}$ and 6 $kW_{p,el}$ and would correspondingly produce 116 kWh_{th} and 52 kWh_{el} during the day of the example (assuming a thermal performance curve as described in [11]). In the example, the outlet temperature at the receiver is fixed to be maximal 90 °C. The temperature at the inlet of the MD is 25 °C and at the inlet of the hot water channel is 85 °C. The MD cycle needs 112 kWh_{th}. The RO with the MD need 12.3 kWh_{el}. This results in a surplus electricity generation of the CPV system of 39.7 kWh_{el}.

TABLE 2. In- and output for the desalination systems for the example case. During the simulated day 4680 l brackish water are used.

Technology	Energy demand	Salinity feed [g/kg]	Output salinity [g/kg]	Recovery ratio [%]	Waste water [l]	Permeate / fresh water [l]
Reverse osmosis	11.3 kWh_{el}	10	49	80	936	3744
Membrane distillation	112 kWh_{th} 1.0 kWh_{el}	14.9	122.5	60	374	562
Total	**112 kWh_{th}** **12.3 kWh_{el}**	**10**	**122.5**	**92**	**374**	**4306**

CPV-T MIRROR SYSTEM

Design of the CPV-T System

To be able to analyze the CPV-T system further a mirror dish system was installed at Fraunhofer ISE in Freiburg. A direct combination with the desalination system is possible and will be tested in the future. Currently measurements at the CPV-T system are used to emulate desalination processes in the laboratory on the basis of the measured power supply profiles.

For the test system, a paraboloid mirror consisting of nine segments (designed and provided by AZUR SPACE Solar Power GmbH) was installed on an existing two axis tracker. Originally the tracker was equipped with FLATCON type modules (CX5000) [9]. The new installation was carefully designed for mechanical stability. The aperture area of the mirror was determined by measurement with a tachymeter, also known as total station method. The aperture area was measured to 15.9 m^2 ±0.07 m^2. The mirror has a focal length of 2.4 m. The receiver is mounted to a carrier designed in a truss construction and secured by steel ropes designed for minimized shading. The CCM receiver can be moved along the focal axis. The CCM receiver is actively water cooled. The temperature of the cooling cycle of the receiver can be controlled. Also the cycle can be connected to the MD through a heat exchanger. Doors are implemented to cover the mirror during non-operation. In Fig. 2 photographs of the CPV-T system are shown.

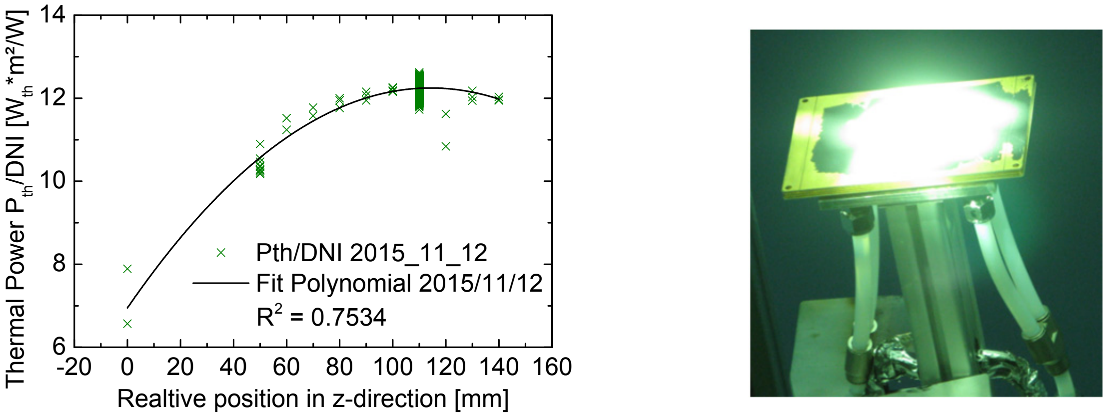

(a) (b)

FIGURE 2. CPV dish system in Freiburg during start-up of the system on 10/11/2015. Left: complete CPV system. Right: illuminated thermal receiver.

Thermal Performance of the CPV-T System

The first operation and start-up of the CPV-T system, has been carried out with a thermal receiver. The receiver was painted in black. Measurements of the mass flow, in and outlet temperatures and solar resources were used to determine the thermal power P_{th} assuming a constant heat capacity of 4182 J/(kg*K) and density of 998 kg/m^3 for the cooling water.

First, the optimum position of the thermal receiver was determined (see Fig. 3). The position of the receiver was moved along the focal axis. The maximum power output was achieved at a relative position of 110 mm, see Fig 3a.



(a) (b)

FIGURE 3. (a) Thermal power of the receiver normalized to the illumination DNI for different relative positions along the focal axis. The measurement was carried out on 12/11/2015. (b) Picture of the illuminated thermal receiver at optimum focal distance.

For this optimum position the thermal performance of the system is presented in Fig 4. The measurements of the thermal power of the receiver normalized to a direct normal irradiance (DNI) of 850 W/m² are shown. Using the measured data we followed a procedure as described in more detail in [10] and [11] in order to reveal a description of the thermal performance description in a theoretical and standardized manner. Therefore, a multilinear regression (equation 1) was solved for the measurement data of 12/11/2015. Thereby losses due to the temperature dependence of the heat loss, variation in wind speed and sky temperature were neglected.

$$\frac{P_{th}}{A_{rec}} = a_0 G_C - a_1 \Delta T - a_5 \frac{dT_m}{dt} \qquad (1)$$

With the aperture area of the receiver A_{rec}, the concentrated irradiation on the receiver G_c the temperature difference between the in- and outlet of the receiver ΔT and the thermal capacitance dT_m/dt, the coefficients were calculated to $a_0 = 0.792$, $a_1 = 384.8$ W/K/m², $a_5 = 178265$ J/K/m². According to this model values for the different measurement conditions can be predicted as shown in Fig. 4. The theoretical maximum efficiency can be determined at a reduced temperature of zero. For our system this efficiency is 79.2 %.

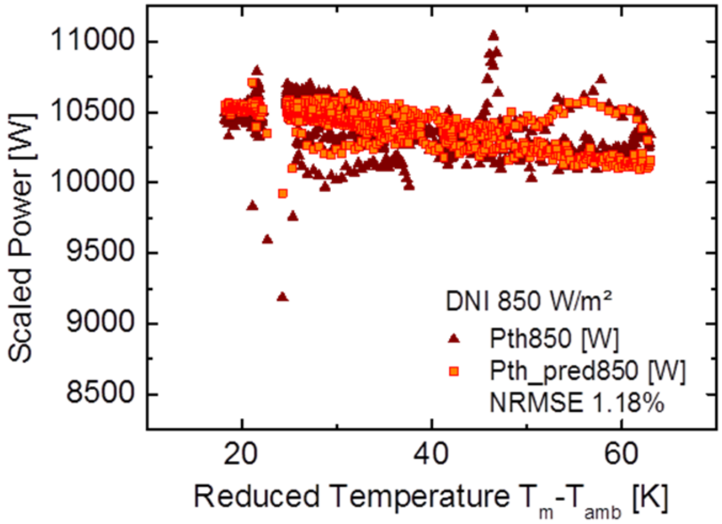


FIGURE 4. The triangles show measurements performed for a thermal receiver on 12/11/2015 between 11:13 – 13:44. Please note that the thermal power is always scaled to an irradiation of 850 W/m². The reduced temperature is the difference between the mean temperature of the cooling fluid between in- and outlet of the receiver T_m and the ambient temperature T_{amb}. The squared points show the thermal performance if equation 1 had been used to calculate the performance theoretically.

CONCLUSION

In this work a system of CPV-T combined with a reverse osmosis and a membrane distillation process for desalination of brackish water is presented. The salinity of the brackish water is increased by the RO with a recovery ratio of 80 %. Then the salinity is increased further by the MD that is driven by the thermal energy provided by the CPV-T system. In the investigated example case, the salinity is increased from 10 to 122.5 g/kg. The total recovery ratio is 92 % for the complete system. This means from 4680 liter brackish water only 374 liter waste water are generated but 4306 liter of pure water and that the combination of CPV-T and desalination system complement very well.

To investigate the system experimentally, a CPV-T mirror dish was installed in Freiburg, Germany. First tests with a thermal receiver showed a very good maximum thermal efficiency of 79.2 % and little heat losses for increased temperature differences between the cooling circuit and ambient temperature.

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