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Experimental analysis of an air gap membrane distillation solar desalination pilot system

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ABSTRACT

A solar desalination system based on membrane distillation (MD) is presented and evaluated. In the context of a European project, the MEDESOL project, a pilot plant was built to evaluate the system, which consists of three commercial MD modules coupled with a static solar collector's field. The MD modules employed have been developed and manufactured by the Swedish company Scarab AB. They have a flat sheet air gap membrane distillation (AGMD) configuration with a total membrane surface area per module of 2.8 m^2. The MD system is intended to be technically simple to operate, robust and able to cover water demands of small settlements. It also contemplates the use of a multi-stage layout to minimize energy consumption.

Experiments were run during solar hours (the layout didn't include heat storage) and addressed to characterize the performance of the system (i.e. distillate production and quality, thermal efficiency and recovery ratio) as a function of operation variables and salt concentration, as well as to identify the operating capacities and the potential improvements of the MD technology. Aqueous NaCl solutions of 1 and 35 g/l concentration were used as feed. Temperatures up to 85 °C in the feed and up to 75 °C in the refrigeration were employed. Maximum specific distillate flux values registered were in the range of 7 l/h m^2. Multi-stage layouts were tested in order to evaluate the improvement of the system's thermal efficiency and recovery ratio. The MD technology assessed proved to be suitable for coupling with transient solar thermal energy but inefficiencies inherent to scaling-up compared to laboratory experiences reported in literature were also identified, namely affecting specific distillate production and thermal consumption. The results of the characterization, performance assessment and operational issues description of the pilot plant are shown.

1. Introduction

The scarcity of freshwater and availability of solar radiation in many isolated regions constitute the perfect condition for applying different solar desalination technologies like solar membrane distillation (SMD) to supply the shortfalls. Nowadays, renewable energy driven desalination technologies are considered suitable for decentralized systems where water demand is lower than 20 10^3 l per day, being the recommended human basic requirements for drinking, hygiene, sanitation services and food preparation in the range of 50–80 l per day and inhabitant [1].

Mathioulakis [2] states that solar distillation is potentially the most suitable option for small sized systems when solar energy is available and distillate is preferred. The particular characteristics of these systems or regions: decentralized services and lack of infrastructures, scattered population and low water demand jointly with hard climate conditions and a general lack of skilled technicians, make it difficult or at least non-cost effective to scale-down traditional desalination technologies, such as reverse osmosis (RO) or multi-stage flash distillation (MSF) designed for industrial-scale water production.

Desalination is a vastly energy consuming process, i.e. RO commercial plants have an electrical consumption between 4 and 6 kWh_e/m^3 and the most effective commercial thermal desalination plants which are multi effect distillation (MED) with a gained output ratio (GOR) of 10–16 have a thermal energy consumption in the range of 40–65 kWh_t/m^3 (equivalent to 18–30 kWh_e/m^3 of electrical power). The spending associated to this energy consumption can mean approximately 30–44% of the total cost of water production [3]. This highlights the necessity for adopting alternative energy sources to drive desalination processes of which renewals are the most

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suitable. Solar energy is being regarded as one of the possible solutions to tackle this energy problem as is considered cheap and accessible and especially suitable in these particular areas [4]. When looking for potential desalination processes that can be appropriate for these areas, some features are more than desirable. The chosen process must be robust in order to stand both hard climate conditions and varying conditions of raw water, should have advantageous attributes regarding the coupling with solar energy (bear unstable operation conditions) and should constitute stand-alone operating systems (practically maintenance-free).

So far, the specific solutions given to tackle this casuistry have been basically two, photovoltaics coupled with reverse osmosis systems (PV-RO) and solar thermally driven distillation systems (STD). Although PV and RO are mature technologies and the most widespread combination used when coupling renewals with desalination [2], with commercial application in many cases [5], there are still some difficulties when operating small scale PV-driven standalone RO systems [6] like the dependence of the chemical pre-treatment on raw water quality and the difficulty to manage it. Moreover, RO operation entails significant automation and has additional needs like accessibility to spare parts and skilled workers [7] which are against the requirements previously stated. Besides, RO systems have the requirements of a continuous process [8] but solar energy is intrinsically discontinuous. Amongst thermally driven systems for small capacities, solar stills are the simplest option because of their practically non-existing operational and maintenance needs and their simplicity of construction. But their main drawbacks are a low yield (the production capacity of a simple type still is in the range of 2–5 l/m^2 per day [9]) and a very low thermal efficiency that results in large specific collector area per cubic meter of distillated water. Their operation is also simple but it is counterbalanced by the problems that arise in the long term, like dust deposition and algae and scale formation, which make the efficiency to be even lower [2].

In this whole context, SMD could be a suitable technology to be explored. It is a thermal separation process which combines the advantages of membrane-based technologies (smaller installation areas) and thermally-driven processes. It is being worldwide investigated for desalination purposes. The main reasons for this are:

- It shows promising results regarding the specific distillate production (up to 80 kg/h m^2) in laboratory scale [10].
- It is a low-demanding process which can be run at atmospheric pressure and at temperatures ranging between 60 and 90 °C.
- It can be coupled with mature, cost-effective and reliable solar technologies, such as conventional static flat plate, evacuated tubes or even small parabolic-through collectors.
- It has potentially low maintenance requirements: membranes used in MD are tested against fouling and as the process is not driven by absolute pressure, clogging risk is much lower than in micro filtration (MF) or RO.

SMD technology is intended to reach better energy efficiencies than other solar desalination processes while keeping an easy and robust operation and potentially low operational costs [11]. MD has been developed since late 60s, but it wasn't until the early 80s, with the improved design of the modules and the development of new and cheaper membranes, that the scientific community became interested in the technology. Recent approaches of coupling MD with low-grade energy have boosted the interest on this technology [6,12–17].

The general objective of this paper is to contribute to the knowledge of solar MD plants operation and performance, more specifically, this work characterizes the thermal performance, the distillate production and quality and the energy optimization of a multi-stage MD pilot-sized system coupled to a field of static solar collectors to be run for a long-term operation.

2. Membrane distillation

MD is a thermal separation process, in which only water vapor or other volatile molecules are transported through a hydrophobic porous membrane. When a temperature difference is created between both sides of the membrane, a vapor partial pressure difference appears, constituting the driving force of the process. This causes the vapor to evaporate from the surface of the liquid/vapor interface of the hot side, pass through the porous membrane and condensate on the colder side. The solely role of the membrane, is to hold the vapor/liquid interface that is created on both sides of it as its hydrophobic nature does not let the water molecules nor the solute ones to pass across it [18–20]. The membrane keeps its hydrophobicity as long as the Liquid Entry Pressure (LEP) is not overcome. This LEP depends on both the membrane characteristics and the surface tension of the solution as it is described in the Cantor–Laplace equation [20]. The desired characteristics of the membranes for MD are basically: a low resistance to mass transfer to help vapor flux, a high LEP to prevent it from wetting and a low thermal conductivity to minimize heat conduction losses and keep the necessary temperature gradient between both sides of it [19,21]. The membranes currently used for MD are designed for MF applications and the operational performances of these membranes are somehow limited for MD [19,22]. There are still few experiences in designing specific membranes for MD. Recent laboratory experiments reached specific fluxes up to 80 kg/h m^2 with enhanced direct contact membrane distillation (DCMD) [10]. These results are promising if they are compared with RO fluxes (between 25 and 40 kg/h m^2, normalized values for nominal conditions) [23,24].

MD has been mostly used in industry to concentrate aqueous solutions of thermally sensitive products like fruit juices, chemicals and antibiotics [25] and also has been employed for wastewater and desalination processes [26,27]. The use of MD for desalination is supported by some advantages:

- It can reach a theoretical 100% rejection of the ions, macromolecules, colloids, microorganisms and other non-volatile particles.
- Its performance is theoretically not affected by salt concentration.
- There is a minimum chemical interaction between membranes and feed solutions.
- It uses lower temperatures and pressures than other thermal and membrane desalination processes.
- It has less space and equipment requirements that result in cost saving.

Even though MD is a promising technology, a small number of practical experiences have been developed in recent years and very few studies dealing with key topics like specific energy consumption, operational issues or long-term performance of MD pilot plants are reported in the literature. Further experimentation can help to overcome the shortcomings that jeopardize its commercial implementation, like its still high thermal energy consumption and the general lack of specific membrane and modules designed for MD purposes.

3. The MEDESOL project

The main objective of the MEDESOL project, which started in 2008, was to develop an environmentally friendly, cost-effective,