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Efficiency in the use of solar thermal energy of small membrane desalination systems for decentralized water production

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HIGHLIGHTS

- Different MD technologies evaluated coupled to solar energy.
- Distillate quality, production rate and energy efficiency analyzed.
- Solar Spring spiral-wound LGMD prototype most efficient of single-stage systems.
- Spiral-wound LGMD and Aquaver V-MEMD showed similar thermal efficiency.
- Concentration factor of V-MEMD one order of magnitude larger than the rest.

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ABSTRACT

The demand of freshwater has surpassed the renewable limit and new water sources are associated with an intensive use of energy. Coincidence between scarcity of water and availability of solar radiation makes solar energy the most suitable option to mitigate the water deficit. This paper analyzes the use of energy for decentralized water production using membrane desalination systems fed with solar energy. An analysis is performed based on experimental results from the most advanced commercial prototypes of different technologies of membrane distillation using various configurations, i.e., air-gap, permeate-gap and vacuum; with flat-plate and spiral-wound membranes. The systems operate with thermal energy, although there is some electrical consumption for pumping and in some cases for sustaining vacuum. The thermal energy requirements per unit volume of water produced are assessed in each case, considering the effect of different operational conditions like the temperature regime and the salinity of the input water.

1. Introduction

Desalination is a process which requires a considerable amount of energy. It must therefore be associated with the use of renewable energy sources for its sustainability [1]. The geographical coincidence between water shortage and high solar irradiance makes the use of solar energy especially suitable [2]. Membrane distillation (MD) is one of the technologies that are being investigated for solar desalination because of its stand-alone features like non-demanding operating conditions, low maintenance requirements and easy automatism features [3]. MD is a thermally driven separation process based on the transport of vapor molecules through a hydrophobic micro-porous membrane [4,5]. The surface tension forces of the hydrophobic membrane prevent liquid molecules to enter the pores, while vapor passes through due to a difference in vapor pressure at both sides of the membrane, which can be established by a difference in temperature. The process rejects theoretically 100% of the non-volatile components, and has the ability to treat solutions with very high salinity. Feed water does not require a strong chemical pre-treatment as for example, the one required by reverse osmosis (RO). Furthermore, MD operates at lower pressures than other separation processes based on membranes, since the driving force is not a difference in hydrostatic pressure. Also, it can perform at lower temperature than conventional distillation since it is not necessary to heat the liquids above their boiling point. Feed temperatures typically range from 60 °C to 90 °C, so low exergy heat sources like low temperature solar energy are suitable for the process.

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Nomenclature

Abbreviations

AGMD	air gap membrane distillation
DCMD	direct contact membrane distillation
LGMD	liquid gap membrane distillation
MD	membrane distillation
PP	polypropylene
PTFE	Polytetrafluoroethylene
RO	reverse osmosis
SGMD	sweeping gas membrane distillation
VMD	vacuum membrane distillation
V-MEMD	vacuum multi-effect MD

Symbols

f	volumetric flow rate (l/h)
F_d	distillate flux collected (l/h m^2)
h_v	latent heat of vaporization (J/kg)
$\dot{m}$	mass flow rate (kg/s)
$\dot{Q}$	thermal heat flow rate (J/S)
SEC	specific electrical consumption (kW h/m^3)
STEC	specific thermal energy consumption (kW h/m^3)
RR	recovery ratio (%)
σ	electrical conductivity (µS/cm)
T	temperature (°C)
ΔT	temperature difference between hot feed and cold feed of the MD module (°C)

Subscripts

c	cold inlet
d	distillate
f	feed
h	hot inlet

The vapor pressure difference across the membrane which drives the MD process can be established using different configurations (Fig. 1). The most simple is when a solution cooler than the feed is in direct contact with the permeate side of the membrane (direct contact membrane distillation, DCMD). The volatile molecules evaporate from the liquid–vapor interface created at the pores of the hydrophobic membrane, pass through them and condense in the liquid–vapor interface created at the other side of the membrane by the cooling solution. The main disadvantage of this configuration is that the direct contact with the cool condensing solution significantly increases the sensible heat losses through the membrane. The latter can be diminished if a layer of stagnant air is introduced between the permeate side of the membrane and a condensing surface in contact with the cooling solution [6]. In this configuration (air-gap membrane distillation, AGMD) however, the air gap increases the mass transfer resistance, so even though the energy efficiency is higher (less conductive losses across the membrane) the permeate fluxes are lower. The reduced mass transfer resistance of AGMD can be avoided if a cold inert gas is used to sweep from the permeate side of the membrane, carrying the vapor molecules outside the membrane module where the condensation takes place (sweeping gas membrane distillation, SGMD) [7]. The sweeping gas can be replaced by the application in the permeate side of a vacuum pressure lower than the saturation pressure of volatile molecules to be separated from the feed solution (vacuum membrane distillation, VMD). In this case the condensation also takes place outside the module and the conductive heat losses through the membrane are reduced even more [8]. However, the risk of membrane wetting is larger due to the higher pressure difference across the membrane. The hydrostatic pressure across the membrane must not exceed the liquid entry pressure of the pores, which has typical values between 1 and 4 bar for commercial membranes and depends on the surface tension of the feed but also on the physical properties of the membrane itself (material, pore size, etc.). Larger values of the hydrostatic pressure break the hydrophobicity of the pores. A further configuration is a variation of AGMD, in which the channel between the membrane and the condensation surface is full of water instead of stagnant air. This is the case when the distillate is left inside the gap at the permeate side of the membrane as it is produced, until it finally comes out of the module by overflowing [9]. This is the Liquid Gap Membrane Distillation (LGMD), in which the conduction losses are reduced compared to DCMD and the mass transfer resistance is lower than in AGMD.

Despite the operational advantages offered by MD, including the potentially excellent distillate quality over the rest of the desalination processes, there are few practical experiences. Most of the studies found in literature deal with theoretical aspects of MD process like heat and mass transfer modeling and lab-scale validation, as well as with the development of new membranes specifically designed for MD purposes [10]. Very promising lab-scale results are found regarding distillate fluxes and quality, but few papers show results of pilot-scale practical experiences and generally they differ from the ones predicted by the models and also from lab-scale results. One of the reasons may be the lack of specific designs of MD modules where laboratory developments are successfully up-scaled. Furthermore, although some commercial applications of the MD technology for desalination or purification of water can be found already in the market, there are few available results of pilot experiences under real conditions. For the industrial application of the technology, further results on practical pilot scale experiences with MD modules and long-time performance are highly necessary. When considering MD powered by solar thermal energy it is important to seek for the highest energy efficiency in order to minimize the energy required and therefore the capital investment on solar collectors for harvesting it. Detail characterizations of the energy performance of real-size MD modules are sparse.

Energy efficiency in MD is diminished mainly by: (i) polarization effects in temperature and concentration; (ii) conduction heat losses through the membrane; (iii) mass transfer resistance within the pores. However, it can be increased by heat recovery. In DCMD and AGMD, the latent heat of evaporation can be recovered by preheating the coolant flow to be used as feed flow on the other side of the membrane (in the latter case, heat from the distillate flow can also be recovered). In SGMD and VMD, condensation takes place in an external condenser and the heat recovery depends on its efficiency. In the case of SGMD, heat recovery is more difficult since a small volume of permeate is vaporized in a large volume of sweep gas which needs to be handled accordingly. Another step on improving the energy efficiency is the design of multi-effect configurations where the latent heat of condensation is reused for several consecutive evaporation processes in several stages of decreasing temperature. This can be done by combining several modules in series or even by designing compact multi-effect modules where the latent heat of condensation in one effect acts as the heat source of evaporation in another effect [11].

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