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Assessment of a pilot system for seawater desalination based on vacuum multi-effect membrane distillation with enhanced heat recovery

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ABSTRACT

This work presents the evaluation of an innovative system based on vacuum multi-effect membrane distillation modules (V-MEMD) for seawater desalination at pilot scale. This four-effect unit introduces a remarkable modification from previous V-MEMD systems, consisting of the use of the seawater feed flow as cooling in the condenser, rather than a separate circuit. Preheating the feed in the condenser improved heat efficiency (maximum gained output ratio obtained for seawater was 3.2). Maximum distillate fluxes reached $8.5\,\mathrm{l\,h^{-1}\,m^{-2}}$ for hot feed temperature 75 °C and feed flow rate $150\,\mathrm{l\,h^{-1}}$. Increasing both parameters to raise the productivity was hindered by the inability of the condenser to cope with all the steam generated in previous effects, resulting in overheating and overpressure. Furthermore, a loss of 40% of distillate production was measured due to the increase of seawater cooling temperature by 8 °C along the year. Finally, it was observed that scaling reduced distillate production up to 50%. Acid cleaning successfully removed scaling and restored the performance. Subsequently, the use of an antiscalant as a pre-treatment was sufficient to prevent it.

1. Introduction

Membrane distillation (MD) is a non-isothermal membrane separation technique [1, 2] with a promising application niche in processes in which low temperature heat sources are applied to the desalination of seawater or high salinity feeds [3, 4]. MD units are usually modular and scalable, and are made of cheaper corrosion-free materials, so the technology can be an alternative to current thermal desalination techniques implemented at large scale. However, MD has not reached yet a full commercial breakthrough. The need to develop prototypes at commercial scale to assess its true techno-economic potential and to comprehend the unforeseeable problems has been pointed out recently by many authors [5–8]. One of the main identified barriers is energy consumption [4, 8, 9]. Several efforts have been made to reduce the energy consumption in pilot scale MD applications. The recovery of latent heat of condensation as sensible heat for preheating the feed has been evaluated by coupling modules in series for the treatment of simulated seawater [10, 11] and wastewater [12]. This requires external devices, which can be avoided by designing internal heat recovery in one single module. This has been proposed using hollow fibre membranes and flat-sheet membranes in spiral-wound configuration. In the case of hollow fibre, only small-scale modules have been tested [13–15]. In the case of spiral-wound, extensive evaluation at pilot scale has been carried out, both in simulated conditions [16–19] and in demonstration plants for producing potable water in remote areas [20, 21]. Currently, multi-channel spiral-wound modules working in air-gap (AGMD) configuration are the ones with the best internal heat efficiency demonstrated at pilot scale, reaching values of the specific thermal energy consumption below $100\,\mathrm{kWh\,m^{-3}}$ for seawater, equivalent to gained output ratio (GOR) larger than 6 [18, 19]. In permeate-gap (PGMD) and AGMD systems, non-condensable gases can decrease the vapour flux in the pores, so they must be eliminated from the feed by deaeration, with the subsequent energy loss [22]. This is avoided in vacuum membrane distillation (VMD). The application of vacuum in the permeate side of the membrane was considered in first studies of MD as a way to facilitate the diffusion of the water vapour inside the pores, and at the same time decreasing the heat conducted through the membrane [23]. Thus, VMD has the highest potential for heat efficiency [24]. However, in VMD condensation occurs at the saturation temperature corresponding to the reduced pressure, limiting the temperature that the cold feed can reach with internal heat recovery, so multi-stage configurations coupling several VMD modules

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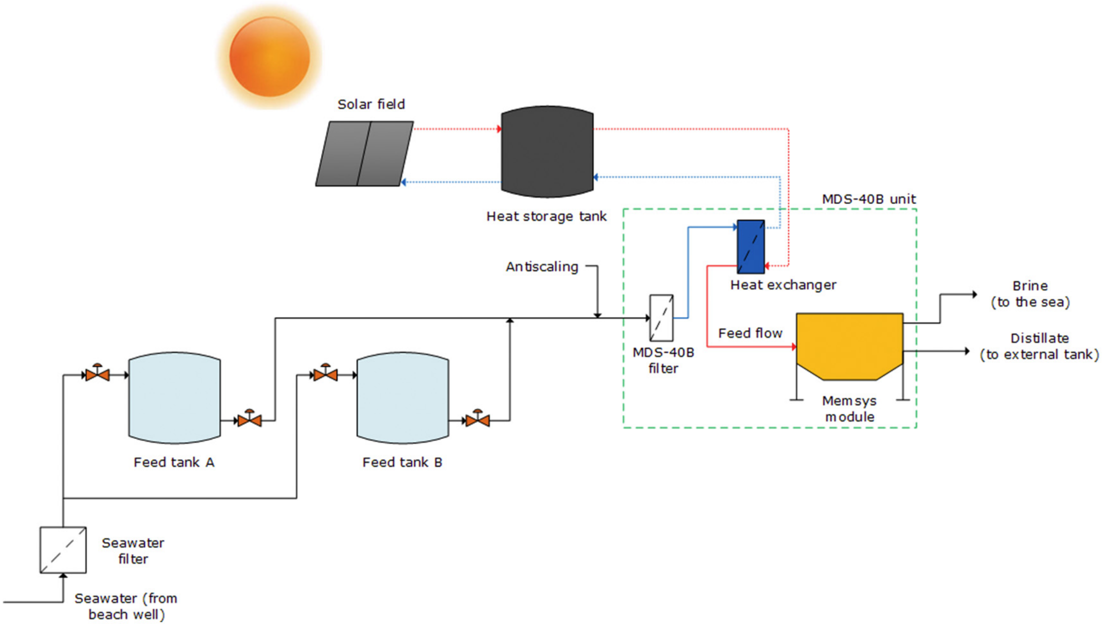

Fig. 1. Diagram showing the main components of the seawater desalination pilot plant.

are required for better heat efficiency [25]. Several multi-stage arrangements for VMD with heat recovery have been simulated. A 24-stage model has been developed by Kim et al. [26] considering hollow fibre configuration and different number of heat recovery units. Other simulation study performed by Chung et al. [27] has been focused on the influence of the number and area of the stages in the energy efficiency of a multi-stage VMD system. Finally, Zhang et al. [28] have performed a thermal analysis of two similar theoretical arrangements with different heat delivery. The only pilot experiment was by Xing et al. [29], testing a three-stage hollow-fibre VMD system with simulated seawater and reaching values of GOR of 2.76.

In all those systems the latent heat of condensation is recovered as sensible heat, thus an increase of heat recovery is associated with a decrease of transmembrane temperature difference and subsequently of the flux [18, 30]. In multi-effect configurations, the latent heat of condensation of the vapour is used to evaporate more feed water in subsequent effects, not only for preheating the feed. As in the case of multi-effect distillation (MED), this means an increase in both productivity and heat efficiency, and therefore the chance of concentrating water sources even more. This concept is exploited in the vacuum multi-effect (V-MEMD) technology, patented by W. Heinzl and commercialized by memsys, who launched their novel plate-and-frame V-MEMD modules in 2010 [31]. Their particular configuration not only avoids deaeration, but also recovers heat for further evaporation in different effects, improving the energy efficiency [32]. A four-effect V-MEMD module has been evaluated with low salt water ($2.3\,\mathrm{mS\,cm^{-1}}$) as feed [33], and with real seawater [34]. Distillate fluxes were 8.1 and $4.8\,\mathrm{l\,h^{-1}\,m^{-2}}$, respectively, but no information was given on energy efficiency. Some studies have been reported on the operation with high salinity, mostly focused on productivity. Aqueous sodium chloride solutions have shown good performance with concentrations up to 3 M in a lab-scale single-effect module [35]. The effluent with concentration $70\,\mathrm{g\,l^{-1}}$ coming from a thermal desalination plant has been treated with the same V-MEMD module, obtaining $4.5\,\mathrm{l\,h^{-1}\,m^{-2}}$ of distillate [34]. In another study, a solution with up to 22.0 wt% of sodium chloride (very close to saturation) has been desalinated during six months using a two-effect V-MEMD module, obtaining a distillate flux of $7.0\,\mathrm{l\,h^{-1}\,m^{-2}}$ [36].

There are not many studies in the literature of V-MEMD dealing with energy use. With a four-effect V-MEMD module, values of GOR below 2 and distillate fluxes up to $1.0\,\mathrm{l\,h^{-1}\,m^{-2}}$ have been obtained in the treatment of 40 wt% calcium chloride solutions for their use as liquid desiccant [37]. A similar V-MEMD system was used in the treatment of up to 22 wt% lithium chloride solutions for the same purpose. GOR was 0.63 and distillate flux was $0.7\,\mathrm{l\,h^{-1}\,m^{-2}}$, because of the low temperature of the heat source and the high boiling point elevation of the concentrated solution [38]. GOR values up to 2.79 and distillate flux of $3.0\,\mathrm{l\,h^{-1}\,m^{-2}}$ have been reported for a four-effect module using real seawater as feed [32]. In another performance study, GOR values between 1.0 and 2.2 and distillate fluxes up to $7.7\,\mathrm{l\,h^{-1}\,m^{-2}}$ have been reported for a four-effect V-MEMD module with prepared feed brackish water [39]. A similar module was used for the concentration of inland saline groundwater from 6.3 to 10.2 wt% as a previous step for a humidification-dehumidification crystallizer. The module yielded $5.0\,\mathrm{l\,h^{-1}\,m^{-2}}$ with a GOR of 3 [40]. Finally, a six-effect V-MEMD module has been evaluated in laboratory studies showing GOR values between 3.2 and 3.82 for seawater feed [41], and values of the specific thermal energy consumption lower than 200 $\mathrm{kWh/m^3}$ (corresponding to GOR values slightly above 4) have been reported for seawater desalination with another six-effect V-MEMD module [42].

In this paper, the evaluation of a four-effect V-MEMD pilot unit using seawater as feed is described, focused on productivity and heat efficiency. This V-MEMD unit incorporates a remarkable modification from the previous V-MEMD systems mentioned above, consisting of the use of the seawater feed flow as cooling in the condenser rather than a separate circuit. This way, the feed can be preheated with latent heat of condensation that otherwise would be lost. This additional heat recovery concept has been evaluated at pilot scale for the first time in this V-MEMD unit. Tests performed during different periods of the year show the behaviour of the system along the different weather conditions. Also, the long experimental campaign allows to analyse the effect of scaling, the cleaning of the membranes and the use of pre-treatment.

2. Materials and methods

The pilot plant presented in this work was designed for the desalination of seawater using MD technology and solar energy as thermal source. It is installed over the flat roof of a building at the University of Almeria, 150 m away from the seashore. The desalination system has three main components: the seawater intake, the solar collection