Desalination 398 (2016) 12–21

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Field evaluation of membrane distillation followed by humidification/dehumidification crystallizer for inland desalination of saline groundwater

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HIGHLIGHTS

- MD-HDH were evaluated as zero liquid discharge technologies for inland desalination
- MD operated on feed salinities of up to 6.3% TDS producing a brine of 10.2% TDS
- HDH was capable of generating solids from the MD brine
- Pretreatment, either by adding antiscalant or acid, was critical for MD operation.
- Total energy input for MD and HDH were 260 kWh/m^3 and 220 kWh/m^3 respectively.

ARTICLE INFO

Article history:
Received 14 April 2016
Received in revised form 4 July 2016
Accepted 6 July 2016
Available online xxxx

Keywords:
Membrane distillation
MD
Humidification
Dehumidification
HDH
Groundwater
Inland desalination
Zero liquid discharge
ZLD
Pilot
Enthalpy balance

ABSTRACT

Membrane distillation (MD) and humidification/dehumidification (HDH) are emerging desalination technologies suitable for inland or "zero liquid discharge" (ZLD) applications. A 1 m^3/d pilot MD system desalinated saline groundwaters with up to 6.3% total dissolved solids (TDS) and produced a brine at 10.2% TDS. This brine served as the feed for a pilot HDH crystallizer.

The MD unit operated at 40% recovery producing distillate with <20 mg/L TDS at a stable flux of 5 L/m^2-h. Pretreatment, either by adding antiscalant or concentrated acid, was critical for stable MD operation. HDH was an effective crystallizer capable of generating solids from the MD brine while producing additional distillate with TDS < 100 mg/L. Total energy input for MD and HDH were 260 kWh/m^3 and 220 kWh/m^3 respectively.

Because cooling water is typically not available at inland applications, removal of latent energy is the key challenge faced by inland thermal desalination processes. This paper also describes the distinctly different processes used by MD & HDH for heat removal and presents an enthalpy balance for a 500 m^3/d MD desalination plant.

Pilot results showed MD & HDH to be technically feasible for inland desalination but both processes need to increase energy efficiency to improve process economics.

1. Introduction

Groundwater is one of the primary sources of water in arid and semi-arid regions where seawater or surface water is not easily accessible. Some groundwater sources have high levels of total dissolved solids (TDS) making it unsuitable for municipal or industrial use [1]. The state of Texas in United States holds ≈2.7 billion acre-feet of brackish groundwater which is equivalent to 150 times the amount of water used in the state annually [2]. Many of these brackish water sources are in hot formations, coming out to the surface at elevated temperatures [2,3]. These groundwaters are sometimes cooled to <45 °C and desalinated for beneficial uses [3]. Two common desalination processes are reverse osmosis (RO) and thermal evaporation [4,5]; however these technologies face their own challenges.

Thermal evaporation processes for inland desalination focus on mechanical vapor compression (MVC) evaporators and crystallizers [6]. Although highly energy efficient, MVC faces high capital cost as expensive corrosion resistant alloys are required to minimize the corrosion caused by high salinity brines at elevated temperatures [7,8].

RO is limited to streams with salinities <4% since above that, the high osmotic pressure required for desalination makes RO impractical [9,10].

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http://dx.doi.org/10.1016/j.desal.2016.07.006
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Also, recovery is limited due to scaling [11]. Additionally, RO is not suitable from treating groundwater with temperatures above 45 °C (without prior cooling) due to the membrane temperature tolerance [12]. For inland desalination, brine must be properly managed since ocean disposal is not a viable option. Possible options for brine disposal are deep well injection or evaporation ponds but these also have their own limitations: i) deep well injection can be environmentally challenging, making their application impractical in some cases [1,13]; ii) evaporation ponds require large footprints and the construction cost with liner and monitoring system is high [1,13,14]. In addition, the water evaporating from the pond represents a lost resource [15].

For inland desalination applications, the efficient option is to adopt zero liquid discharge (ZLD) technologies. In ZLD, the concentrated brine is treated to produce additional desalinated water and dry salts as byproducts, without the discharge of concentrated brines or liquid waste [11,15]. Most ZLD applications use brine concentrators and/or crystallizers, which are energy intensive with high capital and operating costs [13,15]. For sustainable implementation of inland desalination, cost-effective ZLD technologies are required.

In the present investigation, membrane distillation (MD), a low cost evaporator, and humidification dehumidification (HDH), a low cost crystallizer, have been evaluated as alternatives for inland desalination. The desalinated water generated by those processes could be utilized for municipal and/or industrial water supply in remote locations, including the oil & gas industry, where additional water could be suitable for hydraulic fracturing. During hydraulic fracturing, a mixture of water, sand and chemicals is injected at high pressure into the geological formation to create tiny fissures that allow the oil and natural gas to flow through the reservoir and be collected [16,17]. The presence of boron and scale-causing ions (sulfate, calcium, magnesium) in the water used for fracturing poses challenges when utilizing the high salinity groundwater due to interference with the formulation and reservoir compatibility issues.

Another application for the MD-HDH process is for the treatment of the byproduct water associated with the coal seam gas (CSG) production. In Australia, large volumes of water are brought to the surface during the extraction of CSG, this water is treated for beneficial reuse through membrane desalination, generating highly saline brines that need proper management [18]. MD followed by HDH could be an alternative solution to treat the highly saline brine.

1.1. Objective

The primary objective of this investigation was to evaluate the field performance of a MD-HDH process for inland desalination of high-salinity groundwater with ZLD. The performance of the system was evaluated on groundwater from two different wells. The evaluation includes: i) assessment of the process performance, ii) identification and implementation of an effective pretreatment, iii) water quality analyses, and iv) assessment of energy consumption.

1.2. Membrane distillation

MD is an emerging hybrid thermal-membrane desalination process that uses a vapor pressure difference, created by a temperature gradient across a hydrophobic membrane, as the driving force to produce high quality distilled water from highly saline brines [19,20]. The key feature of a hydrophobic membrane is that it permits the passage of gases, including water vapor, but restricts the flow of water and dissolved ions. The passage of water vapor is independent of salinity and hence the process can treat high salinity brines, including brines produced by conventional desalination methods, e.g. RO or thermal evaporation [21]. MD operates at lower temperatures (approximately 85 °C) compared to the conventional thermal evaporation technologies and at lower pressures compared to pressure-driven membrane technologies [22,23].

The primary advantages of MD over RO are [24,25]:

- Can treat very highly saline streams
- Can use waste heat as primary energy source
- Superior effluent quality; comparable to distilled water
- Operates at ambient pressures allowing plastic materials to be used throughout for construction; this reduces cost and corrosion issues

Like any emerging process, MD has potential challenges associated with it, such as, limited experience on scale-up and system optimization [22,24].

There are 4 typical configurations for MD processes: i) direct contact (DCMD), ii) vacuum (VMD), iii) air gap (AGMD), and iv) sweep gas (SGMD) [20]. The most energy-efficient is VMD with partial latent heat recovery, known as “vacuum multi-effect (V-MEMD)” design [22,24]. In this configuration, the membranes are staged and operated at successively higher vacuums to enable the latent heat to be recovered and reused. An MD can also be integrated with a mechanical vapor compressor to eliminate the need for cooling water and to maximize energy efficiency. One challenge faced by MD and other evaporative desalination processes is that the heat added to produce vapor must be removed during condensation. Options for heat removal include vapor compression, cooling water, heat pumps and water chillers [26].

1.3. Humidification-dehumidification

Humidification - dehumidification (HDH) is an emerging thermal desalination process that mimics the natural water cycle by heating water to produce water vapor and then condensing the vapor to produce distilled water [27–29]. HDH is best suited for treating highly saline water (i.e. with TDS > 70,000 ppm) or water that otherwise could not be treated by RO. The waste stream (containing the salts) can be either in the form of a concentrated brine or, with further processing, can be wet crystalline solids (for ZLD applications).

In an HDH process, air serves as the carrier gas for heat and mass transfer. Large fans direct air first through a humidification chamber where warm water is sprayed down onto splash trays. The moist air then flows to the dehumidification chamber where water vapor condenses on a cold surface. The heat released by the water vapor during condensation is used to pre-heat the incoming feed water to minimize thermal energy requirements [27].

The process of evaporation and condensation of vapor is referred as an “effect” and the greater the number of effects, the greater the energy efficiency. The vendor's standard offering features a four-effect design with the last effect acting as a cooling tower [30,31]. The net heat energy input is discharged to the atmosphere as warm moist air [28,29].

The main advantages of HDH processes include [27,28]:

- Operation at ambient pressure & low operating temperature (<90 °C) permits plastic to be used throughout as primary material of construction; reduces cost and corrosion issues
- Can serve either as an evaporator for volume reduction or crystallizer for ZLD applications
- Does not require a source of cooling water or expensive water chillers

The main challenges for the HDH process are high-energy consumption and large equipment footprint [27]. Also, approximately 25% of the feed water is lost to the environment as moist air.

2. Materials and methods

A 1 m^3/d system from one of the leading manufacturers of MD equipment (memsys GmbH, Germany) was pilot tested on highly saline groundwater sources. The concentrated brine from the MD served as a feed for the pilot HDH unit (Saltworks Technologies Inc., Canada).