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Regeneration of dimethyl ether as a draw solute in forward osmosis by utilising thermal energy from a solar pond

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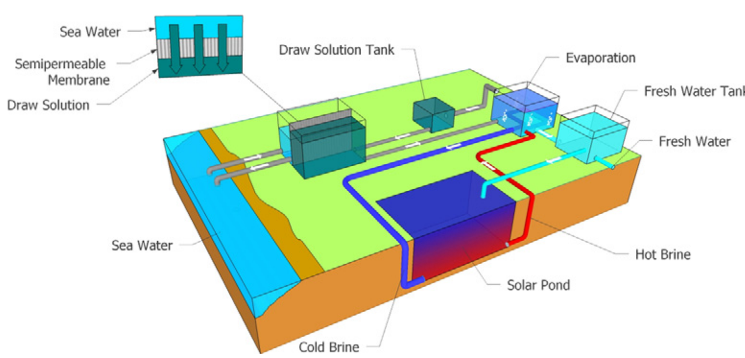
HIGHLIGHTS

- A process is proposed for regeneration of DME as draw solution in forward osmosis.
- Regeneration is carried out using thermal energy from a solar pond.
- The summary of a previously developed model for solar ponds is given.
- The solar pond is simulated for the climatic conditions of Chabahar (Iran).
- Desalinated water over two years is 5210 m^3 given solar pond size of 10,000 m^2.

GRAPHICAL ABSTRACT



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ABSTRACT

Utilisation of solar thermal energy in forward osmosis (FO) can provide an attractive method for seawater desalination. This study presents a novel process for the regeneration of dimethyl ether (DME) as a draw solute in FO using thermal energy from a solar pond. The location considered for this process is Chabahar (Iran) which benefits from a very high solar irradiance and access to an abundance of seawater from the Sea of Oman making it an ideal location for the proposed process. The average daily volume of desalinated water produced using this process coupled to a solar pond of 10,000 m^2 was determined. It is indicated that a solar pond of such moderate size can drive a forward osmosis plant to provide 5210 m^3 of freshwater in the first two years of operation in Chabahar. The proposed process provides freshwater at varying rates throughout the year and benefits from a very low electricity consumption rate of 0.46 kWh per cubic metre of desalinated water offering a viable option for solar desalination. Considering that there are vast uninhabited coastal areas particularly in the Middle East and North Africa (MENA) region, the proposed method can contribute towards addressing the growing potable water scarcity.

1. Introduction

Supplying water for drinking and irrigation purposes is becoming an increasingly challenging task across the globe. Prolonged droughts and excessive utilisation of groundwater resources have led to the prevalence of desalination methods in many countries, as the abundance of

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Nomenclature

A	surface area (m^2)
C	specific heat (MJ/kg K)
E	total solar energy reaching pond (MJ/m^2 h)
F	absorbed energy fraction at δ-thickness
h	solar radiation fraction
HSZ	Heat Storage Zone
K	1, 2, 3, …, 24 (index for time interval Δt)
k	thermal conductivity (MJ/m K h);
NCZ	Non-Convective Zone
Q	heat (MJ)
S	salinity (wt%)
T	temperature (°C)
UCZ	Upper Convective Zone
V	volume (m^3)

Greek symbols

β	fraction of incident beam entering into water
γ	thickness absorbing long-wave solar energy (m)
Δx	thickness of horizontal layers (m)
Δy	thickness of vertical layers (m)
Δt	time difference (h)
ρ	density (kg/m^3)

Subscripts

a	air
b	bottom
c	convection
e	evaporation
fw	freshwater
l	layer
ins	insulation
k	conduction
n	number of day (1–365) in year
S	salinity
s	surface
t	total

seawater presents an almost unlimited resource for many countries. The growing energy and fuel demands along with oil and gas resources becoming more challenging and costly to exploit are leading to scientific initiatives in order to explore novel ways of generating energy. Energy consumption is expected to increase by 37% by 2040 according to the recent World Energy Outlook [1]. In addition, greenhouse gas levels are endangering the global climate [2]. Hence, the employment of renewable sources of energy in water reclamation offers a sustainable method for addressing water scarcity with minimal environmental impact. Amongst those, desalination driven by solar energy has been subject to much development and debate. Such methods are particularly appealing because water scarcity is more prevalent in arid and semi-arid regions of the world where, generally speaking, there are high rates of solar radiation.

One of the simplest and most cost-effective methods in this context is the deployment of solar ponds, which are filled with stratified brine to store heat by trapping solar radiation. The salinity of brine increases with depth and thermal energy is predominantly stored in the deepest region of the pond to suppress heat losses. Solar ponds can be used to drive processes that require low-grade heat [3,4,5].

It has also been reported that given their large storage capacity, solar ponds permit the highest annual operation hours [6] which can be crucial in providing potable water. In addition, solar ponds provide the most convenient and least expensive option for heat storage for daily and seasonal cycles in comparison with other solar desalination systems [7]. The other benefit in desalination coupled to solar ponds is that the waste product from desalination, known as reject brine, can be utilised for the construction of solar ponds, as well as replacing the evaporated brine in solar ponds already in use [8]. This can be a significant factor in reducing the environmental impact of desalination technologies.

There have been several initiatives that combine solar ponds with desalination technologies. A company called ATLANTIS introduced a modified multi-stage flash (MSF) system that is called 'Autoflash' which is coupled to a solar pond [9]. Other plants connecting a solar pond to an MSF process include Margarita de Savoya in Italy with a plant capacity of 50–60 m^3/day, Atlantis in the Islands of Cape Verde with a plant capacity of 300 m^3/day and a research based project in El Paso with a plant capacity of 19 m^3/day [3].

This study aims to demonstrate that the solar thermal energy from a solar pond can drive forward osmosis (FO) desalination using dimethyl ether (DME) as a draw solution. Such a process could substantially reduce electricity consumption in desalination using renewable sources of energy and reduce the quantity of reject brine. A general representation of the proposed process is shown in Fig. 1.

A sustainable solar desalination cycle is therefore introduced and developed in this study. This novel method can contribute towards reducing water scarcity particularly in arid and semi-arid regions of the world where, in general, there are high rates of solar radiation.

1.1. Solar ponds

Solar ponds are used to capture and store solar thermal energy, which can be subsequently utilised for various purposes. The pond is filled with stratified brine (e.g. sodium chloride, magnesium chloride or sodium nitrate solution) ranging from saturated levels at the bottom to almost freshwater at the top. Such concentration gradient aims to

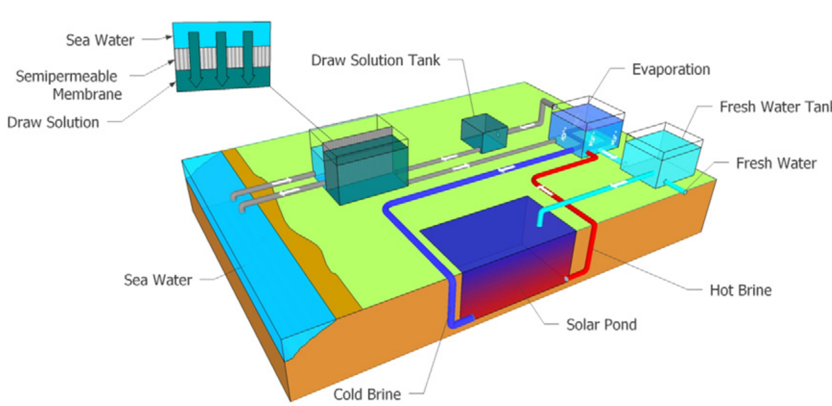

Fig. 1. The proposed process for cost-effective forward osmosis seawater desalination driven by thermal energy provided by a solar pond.