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Assessment of desalination technologies for treatment of a highly saline brine from a potential CO_2 storage site

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HIGHLIGHTS

- Geological CO2 sequestration may generate significant volumes of highly saline brine.
- Existing and emerging high-TDS desalination technologies are critically evaluated.
- Evaporators are identified as the most suitable existing technology.
- Mt. Simon brine treatment by multi-effect evaporation is modeled by Aspen simulation.
- Near-ZLD treatment of Mt. Simon brine requires 246 kWh thermal energy per m^3 of recovered water.

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ABSTRACT

Brine extraction is a promising strategy for the management of increased reservoir pressure, resulting from carbon dioxide (CO_2) injection in deep saline reservoirs. The extracted brines usually have high concentrations of total dissolved solids (TDS) and various contaminants, and require proper disposal or treatment. In this article, first by conducting a critical review, we evaluate the applicability, limits, and advantages or challenges of various commercially available and emerging desalination technologies that can potentially be employed to treat the highly saline brine (with TDS values >70.000 ppm) and those that are applicable to a ~200,000 ppm TDS brine extracted from the Mt. Simon Sandstone, a potential CO_2 storage site in Illinois, USA. Based on the side-by-side comparison of technologies, evaporators are selected as the most suitable existing technology for treating Mt. Simon brine. Process simulations are then conducted for a conceptual design for desalination of 454 m^3/h (2000 gpm) pretreated brine for near-zero liquid discharge by multi-effect evaporators. The thermal energy demand is estimated at 246 kWh per m^3 of recovered water, of which 212 kWh/m^3 is required for multiple-effect evaporation and the remainder for salt drying. The process also requires additional electrical power of ~2 kWh/m^3.

1. Introduction

Carbon dioxide (CO_2) captured from industrial sources can be permanently stored by geological sequestration in deep saline reservoirs. According to a scenario published by the International Energy Agency, Klapperich et al. reported that by 2050, global geologic storage of 9.12 billion metrics tons of CO_2 per year will be required to meet CO_2 emission reduction goals [1]. The U.S. Department of Energy has identified deep saline reservoirs as the largest potential sinks for CO_2 storage in the United States. The total CO_2 storage capacity in major saline reservoirs, estimated by the U.S. Department of Energy carbon sequestration partnerships, is at least 2300 billion metric tons and possibly as high as about 22,000 billion tons [2].

Large-scale geological CO_2 sequestration may result in increasing the reservoir pressure beyond a level that is allowable by safety standards or potential regulations. Brine extraction is considered a promising strategy for managing increased reservoir pressure [3–5]. Significant volumes of brine may be extracted if geological CO_2 sequestration in deep brine reservoirs is implemented at industrial scales. Assuming that each metric ton of injected CO_2 displaces 1.25 m^3 of reservoir fluid, Klapperich et al. estimate that up to 31.2 million m^3 of brine

Abbreviations: CO_2, carbon dioxide; ED, electrodialysis; EDR, electrodialysis reversal; ENRTL, Electrolyte, Non-Random Two Liquid; FO, forward osmosis; GE, General Electric; gpm, gallons per minute; HD, humidification–dehumidification; kWh_{elec}, kilowatt hour electrical; $kWh_{elec\ equiv}$, kilowatt hour electrical equivalent; kWh_{th}, kilowatt hour thermal; LMTD, logarithmic mean temperature difference; MD, membrane distillation; MED, multiple-effect distillation; MEE, multiple-effect evaporation; MJ_{th}, megajoules thermal; MSF, multiple-stage flash; MVC, mechanical vapor compression; ppm, parts per million (mg/L); ppmw, parts per million weight (mg/kg); RO, reverse osmosis; TDS, total dissolved solids; wt%, weight percent; ZLD, zero-liquid discharge.

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Table 1
Comparison of selected water quality parameters of Mt. Simon brine with selected water quality parameters of seawater and brackish water.

Brine/water	TDS (ppm)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Sr^{2+} (mg/L)	Na^{+} (mg/L)	Cl^{-} (mg/L)	SO_4^{2-} (mg/L)	Alkalinity as $CaCO_3$ (mg/L)	pH	Data source
Mt. Simon brine	197,000	22,000	1500	791	48,000	120,000	360	55	7.0	[b]
Seawater at Doha Research Plant	47,000	570	1700	NR[a]	12,300	24,000	3400	175	8.2	[14]
Brackish water at Kantor Desalination Plant	3890	196	146	NR	1014	1970	251	305	6.9	[15]

TDS was estimated by summation of all cations and anions.
[a] NR: not reported but expected to be negligible.
[b] Obtained from the Illinois State Geological Survey Geochemistry team based on previously described methods [12,13].

might be extracted globally each day, although extraction rates may be limited by site-specific factors [1]. Breunig et al. estimate that 2 m^3 of brine will be extracted for every metric ton of CO_2 injected, and that a single CO_2 injection site might receive 8.9 million metric tons of CO_2 per year, resulting in about 48,000 m^3/day of brine extraction [3]. The extracted brines usually have high concentrations of total dissolved solids (TDS), suspended solids, and various contaminants and require proper disposal or treatment. Veil et al. reported the distribution of different water quality parameters of 34,000 brine samples collected from basins that are considered potential targets for CO_2 sequestration [6]. They found that, of 52 formations sampled, 58% of geological formation brines had a median TDS concentration of at least 50,000 ppm, and 23% exhibited salinities >100.000 ppm [6].

The high-TDS extracted brine cannot be discharged to the environment or applied for beneficial uses without proper treatment. The disposal of extracted brine by deep well injection into other formations might not be an option for many CO_2 sequestration sites for several reasons, including the availability of proper geological formations, the high volume of extracted brine, the high cost or other challenges of brine transportation, required pretreatments before brine injection, and environmental regulations. Therefore, treatment of extracted high-TDS brine might be the only practical option for some sequestration sites.

Highly concentrated salt brine effluents are also generated from a variety of sources, including seawater desalination processes, cooling tower blowdown, mine tailing leachate, and produced water from fossil fuel production. The International Desalination Association reported that, as of 2015, there were >18.000 desalination plants worldwide, with a total production capacity of >86 million m^3/day of fresh water [7], about 59% of which comes from seawater desalination [8]. The waste brine effluents from seawater desalination plants are major current sources of high-TDS brine. For instance, the desalination of seawater by reverse osmosis (RO) produces brine concentrates that are typically 65,000 to 85,000 ppm of TDS [9]. A simple assumption of 50% water recovery for seawater desalination plants suggests a brine flow rate of ~51 million m^3/day from worldwide seawater desalination plants. Produced water from oilfields, natural gas, and coalbed methane also generates large quantities of high-TDS brine [10]. For example, the produced water resulting from global oil and gas production is around 250 million barrels per day (~40 million m^3/day) [11].

It is apparent that treatment of brines is increasingly necessary, both for the successful implementation of CO_2 sequestration and for the reduction of waste in other industries. High-TDS brine treatment creates a challenge in water treatment because conventional seawater desalination methods are not designed for feed water streams higher than 50,000 ppm of TDS. In this article, we evaluate the applicability, limits, and advantages or challenges of various desalination technologies that can potentially be employed to treat the highly saline brine (with TDS values >70.000 ppm) and those that are applicable to a ~200,000 ppm TDS brine extracted from the Mt. Simon Sandstone, a potential CO_2 storage site in Illinois, USA. We performed a side-by-side comparison of desalination technologies and selected multi-effect evaporation (MEE) as the most suitable existing technology for treating Mt. Simon brine. We performed process simulations for treatment of Mt. Simon brine for near-zero liquid discharge (ZLD) treatment for 88% water recovery by MEE. We performed material balance for a 454 m^3/h (2000 gpm) brine input unit and determined stream compositions, energy requirements, and other process specifications.

2. The challenge of high-TDS brine desalination

Concentrations of major salts (e.g., salts of Na, Ca, and Mg) are significantly higher in high-TDS brines compared with those in seawater. The high salt content of brine creates specific treatment challenges, such as scaling, fouling, corrosion, and high energy consumption. Scaling and fouling are common problems in desalination processes. Scales are formed when mostly divalent (e.g., Ca, Mg, Sr) species are transformed from soluble to insoluble forms that result from changes in solution chemistry (e.g., pH and composition change) or process conditions (e.g., temperature) during the desalination process. Scales and other suspended solids may precipitate on the equipment surface or separation devices (e.g., membranes) and impede the desalination process by reducing the heat transfer rate in thermal desalination systems or reducing the mass transfer rate through membrane-based systems. Brines extracted from potential CO_2 sequestration sites may have high concentrations of TDS, scale-forming species, and suspended solids. As an example, the composition of a high-TDS brine extracted from the Mt. Simon Sandstone in Illinois, USA, is compared with typical seawater and brackish water, which are the feed streams to conventional desalination plants (Table 1).

The cumulative concentrations of scale-forming cations, mainly Ca, Mg, and Sr, in the Mt. Simon brine are one order of magnitude higher than those of other water samples listed in Table 1. The major divalent anion, sulfate, can form scales with divalent cations under appropriate precipitation conditions. Concentration of total suspended solids in the Mt. Simon brine was measured at our laboratory according to standard method 2540C [16] and is about 2800 ppm, which is up to two orders of magnitude higher than typical values for seawater or brackish water. As an example, concentrations of total suspended solids for selected seawater and brackish water samples is reported as 5–20 ppm [17,18] and 24–144 ppm [19], respectively. Mt. Simon brine may require vigorous pretreatments for the removal of suspended solids and scale-forming species. The pH of sampled Mt. Simon brine is similar to other water sources for desalination. However, we observed that upon extended exposure to air the pH decreased to ~5.5 due to oxidation reactions.

The salinity of Mt. Simon brine or similar high-TDS brines is also significantly higher than the salinity of seawater. Therefore, Mt. Simon brine can be more corrosive to many commonly-used metals. Special corrosion-resistant materials, such as nickel alloys or corrosion-resistive coating, may be needed for pumps, heat exchangers, pipes, or other parts of the desalination systems. Existing seawater desalination processes may need to be significantly upgraded to be compatible with the high-TDS brines.

Even if the technical issues associated with high-TDS brine desalination are resolved, costs may be prohibitive. In addition to higher pretreatment costs and capital costs for corrosion-resistant equipment, energy costs will be much higher for high-TDS brine desalination facilities than for seawater desalination. The theoretical thermodynamic minimum energy consumption for desalination, which sets a baseline for energy efficiency, is dependent on the concentration of the feed