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Sustainable management of hypersaline brine waste: Zero liquid discharge via Joule-heating at supercritical condition

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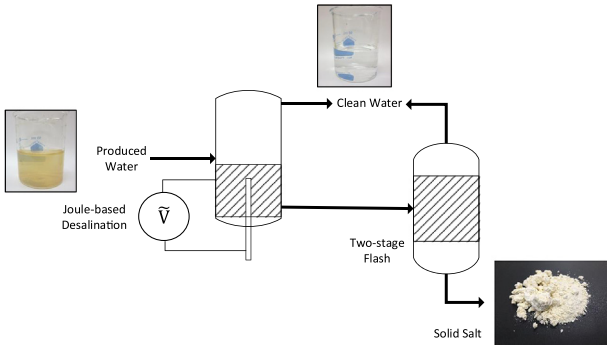
GRAPHICAL ABSTRACT



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ABSTRACT

Supercritical water desalination is an increasingly attractive alternative treatment methodology for hypersaline brine (produced water) waste streams generated by oil/gas wells. The Joule-heating method provided in this study allows for internal heating of high conductivity fluids, reducing thermal lag and heat losses endemic to external heating methods. This study directly compares the aforementioned method for treating field-derived produced water from a Utica-Point Pleasant Shale well located in Noble County, Ohio with previous results using simulated brines. Experimental results from a prototype process are provided at operating pressures of 230 and 250 bar. At these pressures, a clean vapor was produced with total dissolved solids (TDS) levels of 608.73 ± 57.36 and 1174.52 ± 131.3 $mg \cdot L^{-1}$, respectively. The liquid outlet was processed through an additional flash vessel to assess further water recovery, producing an additional clean product with a TDS level of 618.0 ± 34.2 $mg \cdot L^{-1}$. A two-stage flash system model was assessed for the desalinator outlet, introducing a workable design for a zero liquid discharge (ZLD) system at all appropriate brine salt concentrations.

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Table 1
Ranges of aqueous ions within produced water generated by unconventional gas reservoirs, from the USGS database. Data points presented as $mg{\cdot}L^{-1}$; data represented as ppm were neglected [7].

Cations	
Na^+	13.1–117,000 $mg{\cdot}L^{-1}$
Ca^{2+}	1.95–162,324 $mg{\cdot}L^{-1}$
Mg^{2+}	0.1–5560 $mg{\cdot}L^{-1}$
K^+	0.07–4080 $mg{\cdot}L^{-1}$
Ba^{2+}	0.05–22,400 $mg{\cdot}L^{-1}$
Sr^{2+}	0.07–15,400 $mg{\cdot}L^{-1}$
Anions	
Cl^-	1–196,000 $mg{\cdot}L^{-1}$
SO_4^{2-}	0.1–3580 $mg{\cdot}L^{-1}$
HCO_3^-	0.01–13,880 $mg{\cdot}L^{-1}$

1. Introduction

The production of wastewater (produced water) from conventional and unconventional hydrocarbon reservoirs remains the most significant industrial waste byproduct by volume [1]. The USGS Produced Water Database estimates roughly 14 billion barrels (bbl) of the waste is annually generated by oil/gas wells [2]. Estimates indicate nearly $11 billion was spent in 2013 on transporting produced water alone [3]. These produced waters induce multiple strains on the infrastructure and environment, from transportation costs [4] to seismic activity around particular injection sites [5]. Dissolved salts, unreacted hydrocarbons and inorganic compounds make recovery of clean water quite difficult [1]. A 2016 report projects tremendous growth in produced water treatment and recycling, resulting in a $3.8 billion market by 2025 [6]. Sodium chloride is the predominant component within produced water streams as seen in Table 1; however, other primary ions are found including but not limited to Ba^{2+}, Sr^{2+} and naturally occurring radioactive materials (NORM) which magnifies treatment difficulty and associated costs [7]. To prevent production of voluminous solid end products with radioactive or hazardous components, researchers have been investigating various methods to remove such constituents via precipitative and adsorption methodologies [8–16].

Thus, research into effective methods of purifying hypersaline brines to reduce environmental impact and energy production costs will remain. Among the methods commonly employed to treat hypersaline brines, processes with low or zero liquid discharge (ZLD) are becoming more attractive due to their ability to limit costs associated with transport and disposal of concentrate [17]. Nanofiltration and reverse osmosis (RO) membranes are becoming attractive due to their incredibly high recovery [17,18]; however, these methods are typically limited to concentrations of 50 $mg{\cdot}L^{-1}$ and require pretreatment and multiple passes [19]. Produced water total dissolved solids (TDS) content can vary wildly depending upon the source reservoir (as seen in Fig. 1), so a means of treating higher salinity brines with minimal discharge is an emerging concern [7]. For brines of higher salinity, supercritical water desalination (SCWD) has become more attractive to overcome difficulties such as osmotic pressure associated with reverse osmosis [20]. This method has historically been used in organic waste removal [21] but is emerging as a desalination method due to its potential for minimal liquid discharge with hypersaline brines near the salt saturation point [20,22–26]. However, these applications suffer from high capital costs and heat losses due to the heating methods employed [20,24–26], which hinders the scaling of the application from a techno-economic standpoint [27].

To further development of supercritical water technologies to remediate produced water, Ohio University has employed a method utilizing internal Joule-based heating [22]. This method involves an electrode that allows for direct heat conduction within the desalinator vessel, which takes advantage of the high prevalence of conducting salts within a produced water stream. This internal heating method potentially overcomes issues plaguing supercritical water treatment of produced water, including poor heat transfer caused by internal wall fouling and limited scalability due to thick reactor walls [22]. By modulating the conductivity of the contained fluid via phase separation, the applied power is directly proportional to the vapor-to-liquid ratio [22].

This work is a continuation of research evaluating the ability to utilize the Joule heating method to treat simulated hypersaline brines at pseudocritical conditions [22]. In this study, a prototype Joule heating system was used to treat produced water collected from a horizontal well within the Utica-Point Pleasant (UPP) Shale located in Noble County, Ohio. In addition, flashing of hyper concentrated brine generated by the Joule heated system, along with theoretical flash energy balances were completed to provide better overall estimates of clean water recovery.

2. Experimental and methodologies

2.1. Materials

The produced water used in this study was collected from a horizontal well located in the UPP Shale in Noble County, Ohio in April 2017. This particular well was drilled in summer 2011 and brought online in fall 2011. At the well pad, the produced water is separated from the hydrocarbon product and stored in a tank with an inert head space. As the produced water used in this study was collected nearly 6 years after production commenced, this sample is representative of connate water located within the UPP Shale at this location. Upon its collection, the produced water was purged with nitrogen to prevent formation of oxide precipitates. Via analytical characterization (Section 2.3) the produced water was found to contain 255 $g{\cdot}L^{-1}$; to compare to previous studies, the produced water was diluted to 180 $g{\cdot}L^{-1}$ with deionized water. The inlet composition for all trials completed is shown in Table 2.

2.2. Desalination system

The prototype desalination system used herein has been previously described [22]. Up to 300 $mL{\cdot}min^{-1}$ flow rate can be pumped into the system with a high pressure liquid chromatography (HPLC) pump. Once the brine has been preheated via exchange with the liquid effluent and additional preheating, the fluid enters the desalinator, which is equipped with an inner electrode for Joule heating. The desalinator and electrode are constructed from Hastelloy C-276 for high corrosion resistance at the required conditions. The high concentration liquid effluent from the desalinator is subsequently cooled via heat exchange and a secondary condenser, whereas the vapor effluent was condensed prior to a reduction of pressure.

Based on prior work with the described system [22], the desalinator was operated at two pressures (230 and 250 bar) with the diluted field-derived produced water (test solution) described above. Water recovery values of 25 to 40% were investigated within the desalinator at each pressure. Water recovery is determined in Eq. (1),

$$\text{Water Recovery}\ (\%) = \frac{\dot{m}_v}{\dot{m}_i} \times 100 \tag{1}$$

with $\dot{m}_i$ ($g{\cdot}min^{-1}$) as the inlet mass flowrate and $\dot{m}_v$ ($g{\cdot}min^{-1}$) as the vapor mass flowrate.

2.3. Sample analysis

Test solution and desalinator vapor and liquid product compositions were analyzed. A Thermo Scientific iCAP 6000 Inductively Coupled