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A techno-economic assessment of membrane distillation for treatment of Marcellus shale produced water

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ABSTRACT

Membrane distillation (MD) is a promising desalination technology for treatment of high salinity shale gas produced water. Techno-economic assessment (TEA) is necessary for evaluating the economic feasibility of MD for produced water treatment as compared to other shale gas produced water management strategies. A detailed TEA for a hypothetical 0.5 million gallons per day (MGD) direct contact MD (DCMD) that concentrates produced water from 10% (100,000 mg/L) Total Dissolved Solids (TDS) to 30% salinity is presented in this study. The model is developed based on a combination of experimental results, ASPEN Plus process model, best available engineering knowledge, and cost estimates. Analysis reveals that thermal energy cost for MD operation contributes the most to total cost of treating produced water in an MD plant. Additionally, the results of sensitivity analysis reveal that feed TDS level and thermal energy price have a significant impact on total cost of treating produced water. We also explore the implications of utilizing waste heat on the economics of the MD technology for produced water treatment. The results reveal that the total cost of treating produced water using MD is \$5.70/m^3_{feed} which decreases significantly to \$0.74/$\text{m}^3{}_{\text{feed}}$ when MD is integrated with a source of waste heat.

1. Introduction

Desalination has emerged as a promising solution to address the world's water scarcity problem by removing dissolved salts from saline or brackish water, thus making it applicable for a number of uses [1,2]. Membrane separation based processes such as reverse osmosis (RO) and electrodialysis (ED) and thermal processes such as multi effect distillation (MED), multi stage flash (MSF), and vapor compression distillation (VCD) are two main categories of commercial desalination technologies with RO and MSF accounting for 78% of the desalination capacity worldwide [3]. Among thermal based desalination technologies, novel membrane distillation (MD) shows the most promising performance for desalination of high salinity wastewaters [4]. Specially, over the past two decades there has been noticeable improvements in the design of membranes and technical performance of this technique [5]. Prior studies have shown that MD has the potential for achieving up to 99.9% of salt rejection [6–9] and 99.5% of organic materials removal [10,11] where most pure thermal processes or pressure driven membrane processes have limited applicability [12,13], thus making MD one of the most promising technologies for treatment of high salinity wastewaters.

One potential application of MD is for management of high salinity wastewater generated by the rapidly developing unconventional shale gas industry. Unconventional shale gas is a promising energy resource with major economic benefits but is accompanied by a host of environmental challenges including increased level of methane emissions at shale gas production sites [14,15], and the potential for drinking water [16] and groundwater contamination [17]. One of the critical challenges is the management of vast quantities of high salinity wastewater generated in the process of hydraulic fracturing [18]. Shale gas produced wastewater has significantly higher salinity than seawater and also contains various organic and inorganic fractions including dissolved and dispersed oil compounds and dissolved minerals, toxic metals, and radioactive materials [19–22]. Produced water from Marcellus shale play has an average salinity of 100,000 mg/L [23] while typical seawater has salt concentration of 35,000 mg/L [24,25]. This type of wastewater is different from those commonly treated by membrane and thermal based desalination techniques. Subsequently, there is an urgent need to develop new techniques for treating oil and gas industry produced water [19,26–28]. Although treatment techniques such as RO and forward osmosis (FO) have been suggested for treating oil and gas produced wastewater [29,30], their application is expected to be economically infeasible for wastewaters containing more than 40,000 and 70,000 mg/L total dissolved solids (TDS), respectively,

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[31–33] primarily because of the high osmotic pressure requirements [34,35]. MD can treat wastewaters with up to 350,000 mg/L TDS and can operate at lower temperatures (30–90 °C) and pressure relative to conventional desalination technologies [36]. The low operating temperature of MD also makes it ideally suited for integration with renewable energy sources such as wind and solar or low grade waste heat sources [37–40] to make it attractive for treatment of high salinity wastewaters from shale gas activities [36]. This may be of economic interest under rising energy prices as mature commercialized desalination technologies such as MSF and RO require high quality energy sources [41,42].

While MD offers several advantages over other desalination techniques, techno-economic assessment is necessary to evaluate the economic feasibility of MD for treatment of shale gas produced water treatment. To date, little emphasis has been placed on evaluating the economic performance of MD technology for treating produced water. As such, TEA is also needed to develop a comprehensive understanding of the cost drivers for MD treatment of high salinity shale gas wastewaters. It is important to note that cost estimates are site-specific and vary from installation to installation [43] primarily due to differences in system boundaries, site-specific economic indexes, and life expectancy of the project [43]. As such, comparing the results of different studies as well as drawing conclusions based on studies carried out in a different geographic location requires specific consideration as it can significantly change the real cost of treated water [44].

Previous work on TEA of desalination technologies was focused on economic evaluation of seawater purification using MSF, MED, RO, and MD. The unit cost of water production from seawater by conventional desalination technologies is around $\$1.4/\text{m}^3$ of permeate for MSF [45], $\$1/\text{m}^3$ for MED [45,46], and $\$0.5/\text{m}^3$ for RO [47]. Previous studies also report a wide range of cost estimates for desalination of seawater using MD with estimates varying from $0.5\ \$/\text{m}^3$ to more than $15\ \$/\text{m}^3$ of purified water [1,48]. The large difference in cost estimates across studies is attributable to several factors including plant capacity, feed water salinity, and energy sources. Al-Obaidani et al. conducted an extensive exergy analysis and cost assessment for a direct contact membrane distillation (DCMD) unit and identified the most sensitive parameters in MD performance and total cost of water treatment. They performed a TEA for a hypothetical DCMD plant with permeate capacity of $24{,}000\ \text{m}^3/\text{day}$ and estimated a water cost of $\$1.17/\text{m}^3$ for DCMD which can be reduced to $\$0.5/\text{m}^3$ if a low-grade thermal energy source is available [48]. Kesieme et al. evaluated the performance of a laboratory scale DCMD unit for desalination of seawater with an overall recovery of about 90%. They also presented a cost analysis framework and reported a cost of $\$0.66/\text{m}^3$ for a hypothetical $30{,}000\ \text{m}^3/\text{day}$ DCMD desalination plant [1].

Previous studies have also argued that integrating MD with industrial waste heat has the potential for significant improvements in economic viability of this desalination technology. Sirkar et al. operated a small pilot plant for DCMD based desalination using various configurations of membrane modules and membrane surface area in order to study the plant performance. They reported a permeate production rate achieved of $3.38\ \text{m}^3/\text{day}$ for feed rate of $92.67\ \text{m}^3/\text{day}$ and total water cost of $\$0.7/\text{m}^3$ under the assumption that industrial waste heat is available to meet the thermal energy requirements of the MD process [49]. Burrieza et al. performed a TEA for a pilot-scale MD unit ($100\ \text{m}^3/\text{day}$ of permeate) with thermal energy requirements met by solar energy and concluded that solar MD is cost competitive with photovoltaic RO for small plant capacities [50].

While MD holds great promise for treatment of high salinity wastewaters [51], there has been little emphasis on using MD for treating shale gas produced water with only a handful of recent studies focusing on experimental evaluation of MD for treating this water [52–55] and only one study on TEA of MD for oilfield produced water [26]. Macedonio et al. concluded that MD has an overall salt and carbon rejection of over 99% and 90% respectively, for treatment of oilfield produced water and estimated that the total water cost varies from $\$0.72/\text{m}^3$ to $\$1.28/\text{m}^3$ depending on feed water temperature and MD recovery factor [26]. Previous research has also proposed a combination of membrane based techniques for enhancing the performance and economics of water treatment process [26,56–59]. For example, Macedonio et al. have evaluated the economics of seven different configurations of integrated membrane systems including microfiltration, nanofiltration, RO, MD, and membrane crystallization and concluded that adoption of integrated membrane systems provides an opportunity for increasing plant recovery factor, reducing the brine disposal problem, and environmental impacts [60].

The business-as-usual (BAU) strategy for shale gas produced water management is injecting produced water into Class II underground injection control (UIC) wells. However, this strategy has come under increased scrutiny because of heightened seismic activity [61–64] in regions in close proximity to injection wells and potential for groundwater contamination [33]. Underground injection of produced water is also not feasible for shale gas production sites far away from the UIC wells. Finally, with increasing shale gas production, there is a critical need for developing economical and environmentally conscious alternative management strategies for shale gas produced water.

This work presents a detailed TEA to understand the cost drivers and assess the total cost of treating high salinity produced water using DCMD. The TEA is conducted for Marcellus shale play with a specific focus on Pennsylvania primarily due to its limited UIC disposal capacity necessitating produced water recycling and other alternative management strategies. The TEA model is developed by a combination of experimentally determined MD performance, an ASPEN process model, cost data for equipment available in the literature and provided by manufacturers, and best available engineering knowledge. We also performed sensitivity analysis to identify technical and economic parameters that have the major influence on the TEA results. We also assess the impact of integrating waste heat with the MD process on the total cost of produced water treatment. One potential source of waste heat is the heat contained in the exhaust stream of compressor engines at natural gas (NG) compressor stations (CS) with highly understudied waste heat recovery opportunities. Recent work by the authors evaluated the quantity and quality of available waste heat at NG CS and concluded that an average of 43 TJ (terajoules) per day is available in Pennsylvania at temperatures above 645 K [65]. This work serves to add to the sparse literature on the economics of shale gas produced water management in the U.S. by providing a comprehensive economic assessment of MD treatment of produced water in Marcellus shale play as an alternative management strategy to the current practice of reuse for hydraulic fracturing or disposal in Class II UIC wells. It is important to note that although treated produced water could also be used for hydraulic fracturing operations, the quality of permeate generated by MD is well suited for other beneficial purposes such as agricultural or industrial uses. The results from our work provides several important insights including (1) quantifying the total treatment cost of produced water using MD under base case and waste heat integration scenarios, (2) identifying technical and economic parameters with the highest impact on cost of produced water treatment using MD, and (3) comparison of our findings with the BAU produced water management strategy to highlight the potential and limitations of the MD technology for produced water treatment in Marcellus shale play. These insights can be informative to guide decision-making into best strategies for shale gas produced water management.

2. Methodology

2.1. MD experimentation and process description

Produced water samples used for experiments were collected from Marcellus shale region in Pennsylvania. The samples obtained from Tioga and Washington counties have a TDS of 308,300 and 92,800 mg/