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# Integrating membrane distillation with waste heat from natural gas compressor stations for produced water treatment in Pennsylvania

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## HIGHLIGHTS

- Evaluated the potential of DCMD for treatment of produced from shale gas extraction
- Natural gas compressor stations evaluated as the waste heat source for DCMD operation
- Experimental results with actual produced water used for model calibration/validation
- Minimum temperature approach used for the design of large-scale DCMD system
- Sufficient waste heat is available for DCMD treatment of all produced water in PA.

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## ABSTRACT

Direct contact membrane distillation (DCMD) has immense potential in the desalination of highly saline wastewaters where reverse osmosis is not feasible. This study evaluated the potential of DCMD for treatment of produced water generated during extraction of natural gas from unconventional (shale) reservoirs. Exhaust stream from Natural Gas Compressor Station (NG CS), which has been identified as a potential waste heat source, can be used to operate DCMD thereby providing economically viable option to treat high salinity produced water. An ASPEN Plus simulation of DCMD for the desalination of produced/saline water was developed in this study and calibrated using laboratory-scale experiments. This model was used to optimize the design and operation of large scale systems and estimate energy requirements of the DCMD process. The concept of minimum temperature approach used in heat exchanger design was applied to determine the optimum membrane area for large scale DCMD plants. Energy analysis revealed that the waste heat available from NG CS is sufficient to concentrate all the produced water generated in Pennsylvania to 30 wt% regardless of its initial salinity.

## 1. Introduction

Marcellus Shale is a major natural gas (NG) reservoir with steadily increasing production since 2008 that currently accounts for about 40% of the total U.S. shale gas production [1]. Natural gas extraction from Marcellus shale in Pennsylvania, West Virginia and Ohio is accompanied by large amounts of produced water that contains high total dissolved solids (TDS). Future extraction of shale gas requires economical management of wastewater to minimize potential environmental impacts. Produced water injection into Class II Underground Injection Control (UIC) wells is the dominant management alternative in many shale plays with sufficient disposal capacity [2–4]. In the Marcellus shale region, the average cost of produced water transportation from the well site in Pennsylvania to injection wells in Ohio or West Virginia ranges from 10 to 20 $/barrel (bbl) [5,6]. In addition, the costs associated with deep well injection is estimated at $1/bbl [5]. However, while there is a total of 12,000 Class II saline water disposal wells in Texas, only 8 such wells are currently available in Pennsylvania [7]. Lack of sufficient disposal capacity in Pennsylvania requires the development of alternative approaches for management of high TDS produced water [8]. Recent studies have documented concerns over induced seismic activities due to deep well injection [9–12], further emphasizing the need for the development of innovative management strategies for produced water to avoid unintended environmental consequences.

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### Nomenclature

| | |
|---|---|
| A | area of membrane |
| C | membrane distillation coefficient $(\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1})$ |
| $d_f$ | diameter of spacer filament (m) |
| $d_h$ | hydraulic radius (m) |
| E | specific enthalpy $(\text{J}\cdot\text{kg}^{-1})$ |
| h | heat transfer coefficient $(\text{W}\cdot\text{m}^{-2}\cdot\text{K})$ |
| $\Delta H$ | latent heat of vaporization for water $(\text{J}\cdot\text{kg}^{-1})$ |
| H | spacer thickness (m) |
| J | permeate flux $(\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1})$ |
| k | thermal conductivity $(\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1})$ |
| $k_{dc}$ | correction factor for spacer geometry |
| $l_m$ | spacer mesh size (m) |
| M | mass flow rate $(\text{kg}\cdot\text{s}^{-1})$ |
| Nu | Nusselt number |
| p | vapor pressure (Pa) |
| Pr | Prandtl number |
| Q | heat flux $(\text{W}\cdot\text{m}^{-2})$ |
| Re | Reynold number |
| T | absolute temperature (K) |
| TDS | total dissolved solids |

*Greek*

| | |
|---|---|
| $\delta$ | membrane thickness (m) |
| $\theta$ | hydrodynamic angle |
| $\varphi$ | spacer voidage |

*Subscripts*

| | |
|---|---|
| b,f | bulk at feed side |
| b,p | bulk at permeate side |
| f | feed |
| m | membrane |
| m,f | membrane surface at the feed side |
| m,p | membrane surface at the permeate side |

Among different wastewater treatment technologies, emerging membrane distillation (MD) process is particularly attractive because of its low capital investment, low operating temperature, and thus the ability to operate using low grade (waste) heat. MD is a vapor pressure driven process that has been known for over four decades. The first MD patent was filed in 1963 by Bodell [13], while the first paper was published in 1967 by Findley [14]. Direct contact membrane distillation (DCMD) is the most commonly studied MD configuration in which a hydrophobic micro-porous membrane is in direct contact with a hot feed stream on one side and a cold recirculating permeate stream on the other. The volatile vapors from the feed side traverse across the membrane and are condensed on the permeate side. The nonvolatile compounds in the feed stream, such as salts, suspended solids, and macromolecules are retained in the feed solution due to the hydrophobic nature of the membrane. The permeate solution will be free from impurities as long as the membrane is not wetted [15,16] and as long as there are no volatile contaminants in the feed stream that can permeate across the membrane.

DCMD is a non-isothermal separation process that involves simultaneous heat and mass transfer and operates on the principle of vapor-liquid equilibrium. In the last decade, researchers have developed several predictive models for DCMD systems by combining heat and mass transfer principles [17–22]. Heat transfer models comprise of Nusselt number-based empirical correlations to evaluate the heat transfer coefficients [23–25], while mass transfer is typically expressed as a linear function of the vapor pressure difference across the membrane [24–27]. Moreover, different types of heat recovery approaches have been described in the literature [28–32] to recover the energy lost to the permeate side stream from the feed stream and increase the overall energy efficiency of the process. DCMD is being explored for diverse applications such as desalination of water, concentration of aqueous solutions in the food industry and concentration of acids [33–37]. MD processes are able to distill water at operating temperatures of 30–90 °C, which is significantly lower than the conventional thermal treatment processes. The lower operating temperature of MD also offers an excellent opportunity to integrate MD processes with waste heat sources to further reduce the operating cost. Furthermore, MD operates at lower hydrostatic pressure compared to conventional pressure-driven membrane technologies, such as reverse osmosis and nano-filtration [38]. Membrane distillation has been evaluated for desalination of seawater and brine from thermal desalination plants in pilot-scale studies [39–42], but the commercialization of this technology is hindered by high energy cost [43]. Kesieme et al. [44] estimated that the MD treatment cost decreased from $\$2.2/\text{m}^3$ to $\$0.66/\text{m}^3$ when a waste heat source was employed to drive the process. In comparison, the operating cost of reverse osmosis treatment was estimated at $\$0.80/\text{m}^3$ [44].

While many studies reported that integrating MD with waste heat sources can lower its operating cost [44–46], the focus of those studies was often on a qualitative understanding without identifying specific sources of waste heat or conducting a systems analysis to integrate full scale MD technology with actual waste heat sources. Furthermore, there are no studies in the literature that are focused on the feasibility of MD technology utilizing waste heat for treatment of high salinity produced water from shale gas extraction. Relatively abundant and unutilized source of waste heat is available in the natural gas compressor stations (NG CS) in the U.S. [47]. The U.S. natural gas pipeline network is an integrated transmission and distribution network consisting of more than 210 pipeline systems, 300,000 miles of transmission pipelines, and 1799 compressor stations with more than 17 million installed horsepower (HP) for continuous delivery of natural gas [48]. In most CS, a portion of NG is combusted to provide the energy required by the compressor engine that is usually an internal combustion engine or a gas turbine. Despite the high thermal efficiency of compressor engines, about two-thirds of the fuel energy is lost as waste heat [49]. A recent study revealed that a huge quantity of waste heat is available at NG CS in the form of hot exhaust gases [47]. It is estimated that an average of 610 TJ/day of waste heat is released in the hot flue gas of compressor engines in the U.S. at temperatures above 900 K [47]. This offers a potential to collocate wastewater treatment facilities with NG CS to offset the energy requirements of the MD process.

This study evaluated the synergies and potential of MD technology for treatment of shale gas produced water utilizing waste heat available from NG CS. A mathematical model based on the fundamentals of heat and mass transfer processes was developed and calibrated for a DCMD process using laboratory-scale experiments. The model was then used to optimize design and operating parameters for a full-scale DCMD system. The energy analysis from this model was combined with the information about available waste heat at NG CS in Pennsylvania (PA) region of Marcellus shale to estimate the amount of produced water that can be treated in distributed DCMD wastewater treatment plants. Results from this study provide important insights in the operation of an integrated system and can be extended to other sources of industrial waste heat combined with other thermally-driven water treatment technologies.

## 2. Theory and methodology

### 2.1. Mathematical model of DCMD

In DCMD, the hot feed (liquid to be separated or treated) evaporates at the membrane surface and vapors travel across the membrane to be condensed in a recirculating cold liquid on the other side of the membrane. The permeate flux across the membrane can be determined by