Zero-Liquid Discharge Desalination of Hypersaline Shale Gas Wastewater: Challenges and Future Directions

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1. Introduction

Unconventional natural gas extraction from tight shale reservoirs, or "*shale gas*", has recently emerged as an attractive energy resource to face the rising worldwide demand. Over the past decade, advanced technologies of horizontal drilling and hydraulic fracturing ("*fracking*") have allowed the economic viability of shale gas exploration from previously unattainable deposits. Despite optimistic growth projections from the U.S. Energy Information Administration (EIA, 2016a, 2016b), shale gas production is also responsible for worrying environmental and social implications, which are related, among others, to elevated freshwater consumption and hazardous wastewater generation (Thomas et al., 2017).

Within this framework, the application of effective desalination processes is mandatory to treat the large amounts of polluting hypersaline wastewater, alleviating environmental and public health impacts and enhancing overall shale gas process sustainability (Onishi et al., 2017a, 2017b). Hence, the ability of zero-liquid discharge (ZLD) desalination to promote water reuse and/or water recycling (*i.e.*, water reuse opportunities not related to shale gas operations) could be critical for further development of the shale gas industry. This work outlines the challenges and future directions for ZLD desalination of shale gas wastewater.

2. ZLD Desalination for Wastewater Management: Emerging Zero-Emission Technologies

ZLD desalination, as a strategy for shale gas wastewater management, has received increased interest in the past few years. This is mainly due to its capability to comply with the severe regulations on water quality—especially for allowing water recycling or safe disposal—by enhancing freshwater recovery efficiency, while reducing brine discharges (Tong and Elimelech, 2016). Emerging technologies for the ZLD desalination of shale gas wastewater include thermal and membrane-based processes. Thermal-based alternatives comprise multistage flash distillation (MSF), and single/multiple-effect evaporation systems combined with mechanical/thermal vapor compression (SEE/MEE - MVC/TVC) systems (Onishi et al., 2017c). On the other hand, membrane distillation (MD), forward osmosis (FO), reverse osmosis (RO), and electrodialysis (ED), are promising membrane-based processes. Clearly, the selection of the most appropriate desalination alternative is greatly dependent on the wastewater physicochemical composition (Lester et al., 2015).

Apart from the possibility to be operated with low-grade energy sources, membrane-based schemes generally present high water recovery efficiencies, simple scale-up and modular features, and elevated permeability and selectivity for critical components (Drioli et al., 2016). However, thermal evaporation systems can be more advantageous than membrane ones for the zero-emission treatment of shale gas wastewater, as a result of their need for less intensive pretreatment and lower susceptibility to fouling and rusting problems that can be caused by the presence of greases, oil and scale-forming ions (Shaffer et al., 2013).

3. Challenges of ZLD Desalination of Hypersaline Shale Gas Wastewater

Shale gas wastewater generated by hydraulically-fractured wells can present chemical and physical properties varying according to different factors, which include geographic location and formation geology, hydrofracturing fluid composition, as well as its time of contact with shale deposits (Lester et al., 2015; Shaffer et al., 2013). Also, the concentration of chemicals in shale gas wastewater may change over the time of well exploration (Shaffer et al., 2013). In addition to the chemical additives used within fracking fluids, shale gas wastewater generally contains formation-based constituents, comprising salt and other minerals—such as the scale-forming divalent ions: Ca^{2+}, Ba^{2+} and Mg^{2+}—, organic matter and naturally occurring radioactive materials (NORM) (Rahm and Riha, 2012; Zhang et al., 2014).

Among them, removal of the elevated salt contents from shale gas wastewater (average values >100k ppm TDS – Total Dissolved Solids) is notably challenging because of the energy-intensive consumption required to achieve the ZLD brine conditions. In Onishi et al. (2017b), thermal technologies for ZLD desalination (brine discharge at 300 g kg^{-1}) have presented energy consumption in a range of 28.12−50.47 kWh m^{-3}, with specific operational costs estimated between 2.73–4.90 US\$ m^{-3} for 77% conversion ratio. Furthermore, another complicating factor is related to the significant composition variations observed in wastewater from different shale basins, and even in distinct wellbores from the same well pad (Thiel and Lienhard, 2014).

The elevated consumption of high-grade electrical energy is also responsible for significant greenhouse gas (GHG) emissions. Besides the prohibitive costs related to the raised energy consumption, high salt concentrations in the shale gas wastewater pose particular desalination challenges, mostly associated with operational problems caused by fouling, scaling and corrosion (Kaplan et al., 2017). Due to changes in process temperature conditions, fouling and scaling can reduce heat transfer in thermal systems and mass transfer rate in membrane-based technologies. Lastly, appropriate management of the generated solid brine should be considered to avoid potential environmental impacts.

4. Future Directions

Despite of the increasing worldwide interest on the implementation of ZLD desalination systems, their intensive energy consumption and high related operating costs remain as obstacles for their further adoption. Future advances on ZLD applications will ultimately be achieved by the development of more energy efficient and sustainable desalination processes, as well as by incrementing regulatory incentives to compensate eventual economic shortcomings. Eventually, stricter regulations on water quality and brine discharges will play a key role towards the implementation of cleaner ZLD desalination in shale gas industry.

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