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The sweet spot of forward osmosis: Treatment of produced water, drilling wastewater, and other complex and difficult liquid streams

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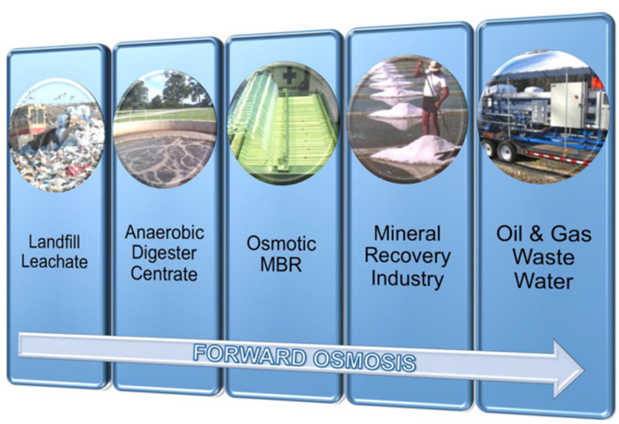
HIGHLIGHTS

- Highly impaired liquid streams can be sustainably treated by forward osmosis.
- Forward osmosis treatment of drilling mud and produced water was evaluated.
- Water recovery >70% was achieved in pilot and demonstration scales.

GRAPHICAL ABSTRACT



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ABSTRACT

Global water scarcity and substantial challenges associated with treatment of complex and impaired liquid streams have advanced the development of forward osmosis (FO), which can successfully treat and recover water for beneficial reuse. Surging research and advancements in FO, a technology once unable to compete with conventional wastewater treatment processes, have identified its sweet spot: treatment and desalination of complex industrial streams, and especially oil and gas (O&G) exploration and production wastewaters. High salt concentrations, decentralized and transient operations, the presence of free and emulsified hydrocarbons, silts and clays leached from producing formations, and process additives common in O&G drilling wastewater and produced water render many common treatment technologies ineffective. Treatment and reuse of O&G wastewater, and other complex industrial streams, in a cost effective and environmentally sound manner is critical for sustainable industrial development and to meet increasingly stringent regulations. This review focuses on the successful development and demonstration of FO membrane treatment systems, supported by a review of bench-scale, pilot, and demonstration studies on treatment of O&G waste streams, landfill leachates, centrate from anaerobic digesters, activated sludge in membrane bioreactors, and liquid foods and beverages. Recent developments in membrane fabrication, system configurations, and draw solutions are briefly reviewed.

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1. Introduction

The United States and many countries around the world are rapidly expanding exploration and development of unconventional gas resources, including shale gas, coalbed methane, and tight sands [1–5]. With recent advancements in horizontal well drilling and hydraulic fracturing, unconventional gas is expected to account for nearly 45% of the natural gas produced in the U.S. by 2035 [6,7]. As production increases and new formations become economically viable, water demands for well development and the volume of wastewater generated during exploration and production (E&P) (e.g., drilling muds, hydraulic fracturing flowback water, produced waters) will increase significantly.

Drilling mud is an integral part of well development, providing lubrication to drilling equipment, stabilization to well walls, pressure control within the borehole, and flushing of debris from the well. Up to one million gallons (3800 m^3 or 24,000 bbl) of fresh water can be consumed during drilling of a single well, producing grit-laden streams contaminated with drilling additives and containing high concentrations of chemical oxygen demand (COD), total dissolved solids (TDS), and organic and inorganic constituents [8–11]. When borehole drilling is completed, the drilling mud is usually stored on-site in lined ponds/pits. In some locations, closed-loop drilling is required in which no pits are used. In most drilling operations, these fluids receive minimal treatment and are trucked off-site for deep well injection. Occasionally, the waste fluids may be land applied if a proper permit is obtained [9].

After drilling, well productivity can be enhanced with hydraulic fracturing. Between one and four million gallons (3800–15,000 m^3 or 24,000–95,000 bbl) of water-based slurry are injected into the well bore under high pressure, forming fractures in the target formation [9,12,13]. Hydraulic fracturing facilitates free flow of oil and gas; thus, increasing recovery from formations previously considered economically unfavorable. A portion of the fracturing fluids that were injected is recovered from the well over a span of several weeks, generating a waste stream of water, sand, and chemical additives [7,13]. Depending on the formation, the flowback wastewater can also have high concentrations of TDS attributed to leaching of earth minerals from the subsurface. Similar to drilling muds, fracturing flowback is recovered and stored on-site. Historically, most flowback water received minimal treatment before being disposed into deep wells [7,9,13]; however, Class II injection wells are not available in all locations. Wastewater treatment is possible, and the treated water can supplement or replace the fresh water necessary for drilling and fracturing of additional wells; yet, highly saline waste streams and some hydraulic fracturing chemical additives are difficult to treat with conventional processes.

The wastewater stream flowing with the gas after most of the fracturing water is recovered, is considered produced water [13,14]. This stream can represent nearly 70% of the total wastewater generated during the lifetime of a well, producing volumes several times greater than the volume of oil and/or gas recovered [15]. The quantity of produced water is highly dependent on well location, and its quality just as variable. These streams typically contain a wide range of TDS concentration, free and emulsified hydrocarbons, and silt and clay leached from the formation [8,16]. Depending on the quality and composition of produced water, a broad range of technologies can be utilized for its treatment; however, the complexity and total cost of treatment is dependent on its salinity and ultimate use [9].

As the development of unconventional oil and gas (O&G) continues in the U.S. and abroad, maximizing water resources while minimizing the volumes of E&P waste will become increasingly important. Several O&G exploration regions are considered at high risk for water resource depletion [8], providing an excellent opportunity for beneficial reuse of reclaimed waste streams. Properly applied management techniques and emerging water treatment processes can drastically reduce industrial water demands, promoting closed loop water recycling and minimizing environmental exposure associated with E&P of unconventional O&G resources.

Many other industrial streams are difficult to manage, similar to O&G E&P wastewaters, and require special technologies to provide sufficient treatment. For example, landfill leachates are heavily contaminated waste streams that often require advanced treatment processes to provide adequate contaminant rejection prior to discharge or reuse. Water recovery from domestic wastewater sludge and anaerobic digester centrate has also gained attention as a result of surging interest in direct and indirect potable water reuse in the United States. The nexus between food production and water recovery has also grown in complexity as the food industry strives to increase liquid food and beverage quality, while simultaneously concentrating these streams. Though each stream is unique and complex, O&G wastewater and other industrial streams can be treated by a small group of advanced processes.

2. Processes for treatment of O&G E&P wastewaters

Chemical, biological, and physical processes have been previously investigated and implemented for treatment of O&G E&P wastewaters; however, high salinity, prohibitive capital cost, extreme chemical demand, large installation footprint, residual (brines and solids) management challenges, and limited removal of emerging contaminants are some of the hurdles to successful implementation of many technologies. Desalination processes such as distillation and membrane separation processes, have demonstrated the ability to achieve adequate treatment of these streams; yet, further improvements to these technologies to reduce the high costs and operational challenges, and development of more effective pretreatment are needed before they are broadly adopted and implemented [10,11,15–18].

2.1. Commercial desalination processes

2.1.1. Distillation

In distillation a feed stream is heated and sometimes also placed under partial vacuum to increase its vapor pressure and form water vapor that can be condensed and recovered as high quality water. Vapor extraction can be repeated several times in the process to enhance evaporation while further concentrating the feed stream. Common commercial distillation methods include multi-effect distillation (MEF), multi-stage flash (MSF), and vapor compression (VC) distillation [19]. Desalination by distillation can minimize physical and chemical treatment and the amount of de-oiling equipment necessary for treatment of O&G wastewater. This eliminates capital costs and minimizes secondary chemical waste sludge [17]. Additionally, distillation can treat highly saline feed streams because it is not affected by the high osmotic pressure of saline and hypersaline streams; however, corrosion and scaling can occur during distillation and incur high operating and maintenance (O&M) costs [14,19]. If volatile organic compounds are present in the feed stream, they may be poorly removed because they will volatilize and condense in the distillate stream. Energy demand is also a limiting factor in distillation, accounting for more than 95% of the total operating costs in a recent review of commercial scale processes [17].

2.1.2. Membrane separation

Membrane separation technologies are commonly pressure driven separation processes that rely on diffusive- or convective-based mass transfer phenomena to separate dissolved and suspended constituents from aqueous solutions. Traditional pressure driven membrane technologies include microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO). Membrane permeability and the size of constituents rejected by each process decrease in the order presented (MF > UF > NF > RO); while MF sieves suspended particles, RO can effectively reject monovalent ions, including sodium, chloride, and low molecular weight organic compounds [17]. Membrane processes, and especially NF and RO, can successfully reject a broad range of contaminants and TDS present in impaired feed streams.