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Review

Challenges and trends in membrane technology implementation for produced water treatment: A review

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ABSTRACT

This review provides insight into the implementation of membrane technology in the petroleum industry for treating produced water that is generated from conventional oilfields in upstream and downstream processes. The ever-evolving and increasingly stringent regulatory standards for discharging produced water pose colossal environmental and economic implications because the bulk of this produced water is disposed into the environment. Thus, a review of the implementation of membrane technology for produced water treatment could contribute to the knowledge required for the increased introduction of scaled-up membrane technology in the petroleum industry. This review encompasses the capabilities and performance optimization possibilities of microfiltration, ultrafiltration, nanofiltration, and reverse osmosis membranes. The level of applications that these membrane technologies might attain within the petroleum industry were determined, and these implementations were correlated with the purpose, performance efficiency, treatment system configurations, necessary pretreatment procedures, quality of treated produced water, fouling occurrence and control, foulants, cleaning procedures, raw produced water content, potential challenges with corresponding applied solutions, and economic factors. This review also maps current and future trends and provides a perspective on the outlook for advances in novel membrane applications for produced water treatment.

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1. Implementation of membrane technology for the treatment of produced water

The use of membrane technology in the petroleum industry began in the early 20th century [1]. Preliminary experiments using membrane technology involved separating certain gases and were initially conducted in 1950 [2]. The pioneer and notable membrane unit was installed in 1977 for adjusting the H_2/CO ratio. Another application that was employed to recover hydrogen from purge gases in petrochemical plants ensued in 1978 [3]. The success of these membrane applications led to the development and application of 219 membrane units in refineries around the world until approximately 1993, after which additional applications have been developed and employed [3]. Currently, the most important membrane applications in the petroleum industry are employed in nitrogen production, hydrogen recovery, natural gas sweetening, nitrogen removal, enhanced oil recovery via CO_2, monomer recovery in polyolefin production, pervaporation processes, and organic solvent nanofiltration (NF) [4]. Such advancements in gas separation technologies have led to the adoption of membrane technologies in liquid-liquid and solid-liquid stream separation processes in the petroleum industry [5]. The first such technology was employed in 1998 at a refinery in Beaumont, Texas, in which the Mobil Oil Corporation installed a reverse osmosis (RO) membrane (e.g., hyperfiltration, originally patented in 1993) [6] to separate small molecules of methyl ethyl ketone solvent from lube oil [5]. This application was also the first recorded industrial use of pressure-driven membranes to separate organic solvent mixtures in the petroleum industry [5]. These RO membranes are solvent resistant (Starmem®) [6] and are composed of Matrimid®. This material is a polyamide membrane that is stable up to 305 °C, and the membrane structure remains glassy and unswollen [5]. Formed essentially as spiral-wound modules, these RO membranes have a flux of 10–20 gal/ft^2/d at pressures ranging from 450 to 650 psi, and their successful application [7–9] has demonstrated the great potential for the implementation of membrane technology in the separation of organic liquids, such as the fractionation of linear from branched paraffins and the separation of benzene and other aromatic compounds from paraffins [5]. Ongoing efforts to optimize the performance of these membranes has achieved recent innovative developments, including the filtration process developed by Exxon that uses an ultrafiltration (UF) membrane [10] system (patented in 2009) to upgrade visbroken residual products by UF during thermal cracking [11] and the production of an enhanced residual coker feed using an UF membrane [12]. Two novel applications [13,14] that exemplify membrane process applications in the petrochemical industry were patented in 2009 [4].

Recent advancements have demonstrated the potential for applying available commercial modules of such membranes to produced water management in the petroleum industry. Successful applications of such membranes in the gas separation and desalination industries have demonstrated the reliability of these technologies. To exploit their reliability, the most recent application of membrane technology adopted in the petroleum industry involved the treatment of produced water through pressure-driven membrane technology [4]. Tremendous advancement and expansion in oil production and refining have resulted in the consumption of vast quantities of process water and the consequent generation of vast amounts of wastewater, termed produced water [15]. Existing management options for produced water are currently restricted to re-injection, reuse or recycling, and discharge [16], which are all heavily governed by regulations due to the complexity of produced water contaminants [17]. Currently, traditional methods of produced water management do not adequately satisfy the petroleum industry requirements for treating produced water in compliance with discharge and reuse standards [18,19]. Thus, there is a substantial need for innovative membrane process technologies. To this end, this review highlights the on-going implementations of pressure-driven membranes in the petroleum industry for treating produced water generated from conventional oil sources, as 85% oil is extracted from such sources [20]. The existing literature regarding these processes and recent advancements in membrane technology applications in the petroleum industry for produced water treatment is insufficient [19,21–26]. Hence, to bridge this research gap, this review has screened the available literature to focus on different types of microfiltration (MF), UF, NF, and RO membrane processes for treating actual produced water that originated from conventional oil resources and treated at the bench and industrial scales. In addition to the drivers of such membrane processes and their performances, current trends and future prospects are discussed. Therefore, this review of membrane technology applications for produced water treatment in the petroleum industry contributes to the expansion of such membrane applications in treating produced water during different processes of oil production and refining. This review may assist in advancing the industrialization of membrane technologies in produced water treatment and improving the understanding of current practices in management by shifting the current view from produced water as merely a source of pollution to its role as a renewable water resource. Thus, this review aims to assist in intensifying more effective produced water reuse efforts by employing membrane technologies.

1.1. MF membranes

Several MF membrane studies were reviewed to establish the characterization and effectiveness of MF membranes for produced water treatment. A ceramic MF membrane for treating produced water was reported in 1997 [27]. Two α-alumina ceramic membranes with pore sizes of 0.2 and 0.8 μm and one modified ceramic membrane surface composed of polyacrylonitrile (named 1MF, 2MF, and 3MF in this paper) were used to microfilter produced water containing high levels of oil (up to 1000 mg/L). Mueller et al. [27] claimed 99% removal efficiency using MF membranes that were supplied by Membralox and Zenon Environmental in tubular modules (Table 1). The membranes were operated at low pressure (0.69 bar), and the following ranges of permeate flux values were obtained for the MF membranes: MF1, 471–26 kg/m^2 h, MF2, 301–25 kg/m^2 h, and MF3, 438–6.9 kg/m^2 h. This study reported that solutions of NaOH (0.2 wt%) and nitric acid (1.0 wt%) were applied for the chemical cleaning of MF1 and MF2 membranes, whereas a caustic anionic detergent (pH 12.1) and citric acid (pH 1.4) were used to clean the 3MF membrane. Neither one of these cleaning procedures was effective in cleaning the MF membranes after utilization with high concentrations of oil, which caused significant fouling and resulted in no recovery of flux (Figs. 1–3). The modeling of the fouling mechanisms in Fig. 4 for the 1MF and 2MF membranes showed that they were internal and external, respectively, whereas 3MF only exhibited external fouling due to the high presence of foulants in the form of submicron-sized oil droplets. Furthermore, varying the operational conditions did not significantly affect the fouling mechanisms, thus indicating complete blockage of the MF membrane pores; the analyses of the fouling layer thickness demonstrated that layer thicknesses of 60 and 30 μm covered a 0.2 μm ceramic MF membrane and a 0.1 μm PAN-MF membrane, respectively (Fig. 4). Such fouling layer thicknesses require a pre-treatment step before processing ceramic MF membranes for produced water treatment [27].

Six years after this study, Zhong et al. [28] developed a new generation of ceramic MF membrane composed of zirconia (ZrO_2). Produced water containing maximum oil concentrations of 200 mg/L was first mixed with flocculation as a pretreatment and