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Electrodialysis-based desalination and reuse of sea and brackish polymer-flooding produced water

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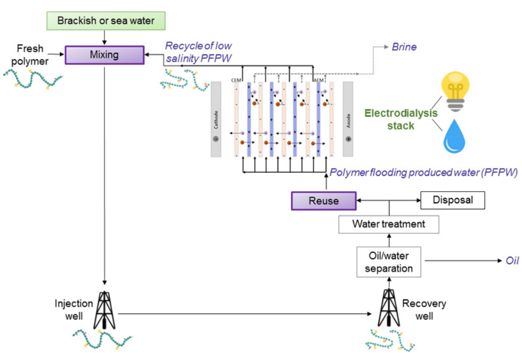
GRAPHICAL ABSTRACT



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ABSTRACT

The reuse of polymer flooding produced water (PFPW) generated in oil and gas industry is limited by its salt content, making desalination by electrodialysis a promising treatment option. Therefore, this study aimed to 1) assess the technical feasibility of employing electrodialysis to desalinate PFPW generated in assorted scenarios, and 2) evaluate the reuse of the electrodialysis-desalted water to confect polymer-flooding solution. The experimental work involved desalting two kinds of synthetic PFPW solutions, one with relatively low salinity (TDS = 5000 mg/L, brackish PFPW), and another with high salinity (TDS = 32,000 mg/L, sea PFPW), at two different temperatures, and later reusing the desalted solution to prepare viscous solutions. For the electrodialysis runs, the effects of feed composition and temperature on water transport, energy consumption and current efficiency were analyzed. It was found that the presence of polymer did not significantly influence the water transport rate or the specific energy consumption for the seawater cases, but had a measurable effect when desalting brackish water at 20 °C. It was also found that some polymer remained in the stack, the loss occurring faster for the brackish PFPW. Still, both kinds of reused PFPW probed adequate to be employed as a basis for preparing n polymer solution.

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1. Introduction

1.1. Polymer flooding produced water

Polymer flooding is a method for chemical enhanced oil recovery (cEOR) that relies on the use of polymeric solutions to increase the recovery of hydrocarbons from existing oil fields. It is currently applied in several projects around the world –including countries like China, India, Oman, Angola, USA, Canada, United Kingdom, and Brazil– and its use is predicted to increase since both energy and oil demand will keep growing during the following decades, while finding new oil fields becomes increasingly challenging and costly [1–4].

Polymer flooding consists in employing displacing fluids with high viscosity, which consequently reduces the mobility of the aqueous phase and the water/oil mobility ratio, and finally leads to an increase in the macroscopic displacement efficiency [5]. In practice, this means that large volumes of water viscosified with polymers are pumped through an injector well in order to sweep the remaining oil and increase its recovery. The produced stream is later recovered in a production well and split in a gas, an oil and a water stream; the latter better called polymer-flooding produced water (PFPW) so to distinguish it from other produced water without polymers.

Depending on the geographic location of each project, the water for preparing the polymeric solution can be taken from different sources, therefore varying extremely in composition and salinity. As a rule, offshore projects rely on seawater as main water source, while onshore projects can have access to a variety of water sources. Recently, Henthorne et al. [6] published a survey about the source of injection water for over fifty EOR projects, including besides polymer addition, other chemical and thermal methods: most common source of water used was produced water itself (over 50% of the cases) followed by seawater (40%). The authors also reported that the salinity range of the water employed (57% of cases) was between 10,000 and 50,000 total dissolved solids (TDS), followed by lower salinity waters in the range of 1000 to 10,000 TDS (23%). For the specific case of polymer flooding projects, Standnes & Skjevrak [7] summarized the characteristics and results of 72 polymer flooding projects implemented around the world. Considering only the projects for which the polymer injection water quality is clearly stated, > 50% reported employing fresh water for the polymer preparation, 22% reported using produced water and 15% made use of high salinity water. Even though fresh water appeared as the preferred option, it must be considered that many of the evaluated projects were carried on during the 1960's to 1980's, but in contemporary conditions of growing water-scarcity and increasingly stringent legislation, it is foreseen that present and future EOR projects will become more dependent on produced water as a main supply source for their daily operation, including the make-up of polymer solutions. For example, state regulation in Oman forbids oil and gas companies to use fresh water reservoirs (including shallow aquifers) for oilfield development, so the operators in the country currently rely on deep groundwater and produced water as supply sources [8,9].

Legislation and environmental concerns do not only play an increasingly important role in the accessibility to water sources, but also in the selection of disposal methods for EOR produced water. Even in non-water-stressed regions, the discharge of PFPW has to adhere to progressively stringent regulations, making reuse a more and more appealing option [10]. For example, according to the United Kingdom law, the most commonly employed EOR polymer does not pass the standard biodegradation test, so the base case for any polymer flooding project in the country is currently that water that potentially contains traces of polymers cannot be disposed of and needs to be re-injected [11]. With more stringent regulations, it could be even possible that the practice of EOR produced water discharge may be phased out, forcing closed loop recycling [1]. Consequently, the reuse of produced water and PFPW in different EOR applications is being assiduously evaluated [1,12].

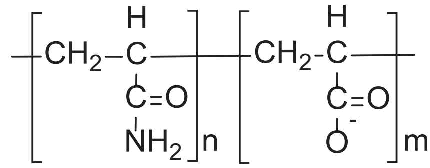

Fig. 1. Partially hydrolyzed polyacrylamide (HPAM) molecule.

Among the different reuse options, the use of PFPW to confect new polymer solution results threefold beneficial since it would minimize fresh water consumption, reduce the pollution caused by PFPW discharge and guarantee a reliable supply of water for the EOR projects [13]. In order to serve for reuse purposes, produced water is required to go through a series of operations to remove reuse hindering contaminants. Compared with the conventional produced water, PFPW contains not only crude oil, minerals, and bacteria, but also residual polymer. This makes treatment with commonly used methods difficult. Even after treatments such as flotation, coagulation, sedimentation, sand filtration and ultrafiltration, PFPW still contains residual organics and relatively high salinity (ranging from 2000 to 150,000 ppm), the latter making the mixture inadequate for reuse in EOR [14,15]. This is because the most employed viscosifying polymers are high molecular-weight polyelectrolytes – like partially hydrolyzed polyacrylamide (HPAM, Fig. 1) and its derivatives – which are sensitive to the presence of ionic species in solution – salt, alkali, or ionic surfactants. These ionic species have the effect of shielding the natural repulsion between the negative charges of the carboxylate groups of the HPAM, reducing the hydrodynamic size of the polymer molecule [16], and consequently lowering the viscosity of the solution. Thus, for produced water to be reused to confect polymeric solution, reduction of the salinity is highly desirable. Indeed, it has been suggested that the ideal water salinity for this purpose is in the range of 500 to 1000 ppm, due to potential swelling and incompatibility with the reservoir formation [17].

1.2. Electrodialysis to desalinate PFPW

Currently, two types of processes are relevant for the desalination of produced water: thermally-driven processes - that include multistage flash evaporation, multiple-effect distillation and vapor compression evaporation,- and pressure-driven processes such as reverse osmosis (RO) and nanofiltration [18–20]. While each method possesses its own advantages and drawbacks, in this particular case they all share one inconvenience: production of a water stream very low in TDS, and a rejected stream concentrated in salts and organic matter. While the latter is problematic because it still poses disposal issues, the former does not have the adequate salinity to be reused in EOR, as previously explained.

This explains why electrodialysis (ED), a salt selective technology, has been recently proposed to reduce the salinity of the PFPW stream [21]. In the reuse scheme, this would have the highly desirable effect of reducing the amount of fresh polymer and chemicals required to reach the target injection viscosity. Other potential benefits of including a partial desalination step are the reduction of scaling along the injection system, a decreased risk of reservoir souring, and a diminished polymer contamination in the produced streams [22].

As stated before, the application of electrodialysis to desalinate PFPW is relatively recent (first documented ten years ago), and has been focused in PFPW from the Daqing field in China [21,23]. Until now results seem promising, leading to the construction of a 9600 t/d water treatment ED setup [24] and further studies addressing fouling of the ED membranes [24,25]. However, as EOR and polymer flooding are being applied in increasingly diverse scenarios, the variety of the generated PFPW is therefore also growing. For example, PFPW of salinities between 5000 TDS and seawater levels are abundant streams whose treatment with ED has not been reported. Therefore the reuse of these