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Cost assessment and retro-techno-economic analysis of desalination technologies in onshore produced water treatment

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ABSTRACT

Due to stricter environmental regulations and lack of other alternatives, saline effluents reuse is becoming necessary in arid regions. Produced water generated in oil and gas exploration is a promising stream for this purpose, since remarkable quantities are available. In order to turn desalination routes into economically attractive options, it is mandatory to choose and to optimize technologies aiming to minimize capital and operational costs. Therefore, several combinations of technologies, involving forward osmosis (FO), reverse osmosis (RO), assisted reverse osmosis (ARO), microfiltration (MF), mechanical vapor compression (MVC), and membrane distillation (MD) were simulated and optimized for different reuse destinations. Results indicated MF-RO as the cheapest route for salinities lower than 90 g/L, while FO-RO had the highest cost and could be unfeasible depending on salinity. For higher salt content, MF-ARO-RO was the cheapest alternative, followed by thermal processes (MF-MVC and FO-MVC, respectively). However, applicability of MVC depends on final water quality due to possible volatiles constraints. MF-ARO-RO process, which is a novel technology, was submitted to a retro-techno-economic analysis (RTEA) to investigate its potentialities. Although membrane parameters had minor influence, external parameters as ARO membrane cost, energy cost and interest rate play important roles on process cost.

1. Introduction

Great amounts of produced water are generated in oil and gas (O&G) exploration, handling and processing. These quantities can be more expressive than oil production itself, mainly in mature fields, reaching values higher than 90% of the outlet stream [1]. Generally, blue water can also be required the most in the later years of an oilfield, mainly for secondary and tertiary recoveries. An aggravating circumstance for water management in O&G facilities is the development of unconventional sources (as shale gas and oil and tarsands), which can be even more water-intense than conventional ones, not just during the production but mainly during drilling and fracking [2].

As effluent discharge or water intake constraints can limit industrial capacity of O&G operations in water-stressed zones or under stricter environmental regulations, produced water reuse by desalination may be an economic option. Brazilian Northeast semi-arid region, where there is most of onshore oil production in the country, have been experiencing extreme droughts over the past years [3]. This condition led to water restriction to cities, crops, energy generation and industrial activity [3]. At the same time, onshore oil exploration in this region is both a water consumer and an expressive effluent generator, since the oilfields are predominantly mature.

Produced water, as the main effluent of oil exploration, is a water source which can be valuable for oil production as well as local uses. Treatment and discharge unit cost for produced water can vary from 0.15 US$/m^3 to 15 US$/m^3 [4], depending on the oilfield and water destination. Although final water quality has an influence in treatment cost, specific disposal costs can describe a scenario in which reusing is a cheaper approach. On the other hand, stricter disposal restrictions and water supply limitations can also restate produced water reuse as an attractive, or even mandatory scenario [5].

Several papers have been addressing produced water reuse for potable [6], irrigational [7] and fracking purposes [2]. Treatment often includes oil and organics removal, and sometimes, desalination [1,6,8]. For the latter step, recent approaches have been focusing on forward osmosis, that can be coupled with thermal recovery [2,9-11], and membrane distillation [12–15], mainly when there is low grade heat available.

At the same time, new technologies modifications for seawater and saline effluents are being investigated. Membrane distillation to

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enhance recovery in mechanical vapor compression was proposed for seawater desalination [16] and could lead to savings also in produced water treatment. Another promising modification is the use of RO assisted with draw/sweep solution. This solution was proposed as an alternative to minimize vessels working pressure for seawater [17] and minimizing energy consumption compared to thermal processes [18,19].

Regarding to energy consumption, which is a major concern in high salinity applications, Thiel et al. [20] evaluated electrical and thermal energy inputs for several technologies, showing significant comparison results. The needed theoretical energy for RO is much lower than other thermal and membrane processes, from conventional to new ones, even for high salt content. As these processes vary in material and design, it is mandatory to compare them not just in energy terms, but also in economic assessments. Although energy consumption [11,20] and sparse desalination cost [4,12,15] have been discussed for produced water, there is a lack of cost comparative analysis for produced water routes. This is a mandatory issue, since pressure ratings or the absence of available heat, for example, can culminate in prohibitive costs.

Thus, the main objective of this paper is to address an analysis on process variables and costs for desalination processes applicable to a specific case study of produced water in a Brazilian onshore oilfield, aiming to choose most suitable routes and to investigate new technologies limitations by a retro-techno-economic analysis [21].

The available technologies for desalination are discussed, as well as Brazilian produced water characteristics and its most suitable reuse options, which can affect process design choice. In the next topic, proposed desalination routes and its main variables are presented and justified. Further information on modeling of each step can be found in Supplementary material. After introducing the optimization strategy and the concept of retro-techno-economic analysis, the results on cost and energy are examined and guidelines are discussed.

2. Modeling framework

In produced water treatment, many technologies have been proposed for removal of oil and grease [8,22,23]. In the case of desalination processes, suitable technologies are similar to those applied to seawater treatment, as multistage flash (MSF), multieffect distillation or evaporation (MED or MEE), MVC, RO and recently, MD [7,14,24].

As stated by Ettouney et al. [25], MSF and MED have higher capital cost. Additionally, they are potentially more expensive in terms of energy cost than RO and MVC and are usually coupled with cogeneration plants [24,26], that is not commonly the case of produced fluids treatment. It is worth to highlight that thermal or hybrid technologies are usually more suitable when there is a heat source availability and could be good options for specific cases, as membrane distillation for oilfields which use Steam Assisted Gravity Drainage (SAGD) [12]. However, as the present case study does not have available low grade energy, only MVC and RO were chosen to represent conventional technologies in this study, since both processes need an electrical energy source only. Another point of interest was to analyze whether RO would still be the cheapest option even with a maximum pressure constraint, in accordance with Thiel et al. [20], who showed that this process has the lowest energy consumption.

For route design, this paper considered an onshore produced water with salinity of 90 g/L and oil and grease of 100 ppm [22]. Even though this effluent was assumed to be a sodium chloride solution, it is important to stress that there can be also organic matter and scaling salts in produced water, as shown in Table 1. As the main objective is to evaluate differences in routes cost caused mainly by colligative properties and separation principles (as hydraulic pressure or temperature), other contaminants/parameters were not modeled. However, in real operation, these contaminants can negatively affect system performance or even require specific treatment [7,20,25,27].

Not only feed water quality, but also product water quality can influence suitability on certain desalination routes. Aiming to investigate the more common destinations in an onshore oilfield, this paper considered three main options of reuse: irrigation, livestock and industrial water. Despite the fact that each one has several constraints, as toxicity, scaling potential and others, this work only considered total dissolved solids (TDS), assumed to be equal to salinity, and total oil and grease (TOG) limits.

Table 1
Physical and chemical parameters for Brazilian produced waters.

Parameter	Value	Reference
Sodium (g/L)	18.9–36.8	[28–30]
Chloride (g/L)	22.5–58.9	[28–31]
Calcium (mg/L)	769–2500	[28,31]
Magnesium (mg/L)	678–730	[28,29]
pH	6.3–7.3	[28,31]
TOC (mg C/L)	113–386	[30,31]
TDS (g/L)	77.8–98.8	[30,31]

For the three studied reuse options, oil and grease concentration should be zero. Water for irrigation and livestock were limited at 2000 mg/L and 5000 mg/L of TDS, respectively [32–34]. Industrial water was assumed to have TDS of 200 mg/L, according to oil companies corporate data on main water users.

2.1. Proposed technologies and economic assessment

To achieve the desirable compositions, combinations of technologies were analyzed. In some alternatives, microfiltration was applied as pretreatment for oil removal, and in others, forward osmosis was employed, since it has been proposed to this specific purpose [2,35,36]. Aiming to standardize quality and quantity for a fair analysis, in cases in which treated water salt concentration was much lower than needed, this desalted water was blended with microfiltrated water. This stream was used to increase the final mixture salinity to achieve the required quality, characterizing a bypass of the desalination stage.

Another important consideration is the absence of progressive fouling, due to difficult quantification, which causes lack of performance in membranes or heat exchange equipment. Besides, as there can be draw solute loss or gain in assisted processes, proposed routes were considered to be in steady state operation by adding a makeup stream or drain, also considered in operational costs.

For costs analysis, all equipment expenses were considered at year 2016 and the equipment cost equations were corrected using Chemical Engineering Plant Cost Index (CEPCI) [37]. Additionally, membrane modules (FO, RO and ARO) were simulated using finite volumes for better detailing. Combinations of processes were simulated in EMSO (Environment for Modeling, Simulation and Optimization), which is an equation-oriented process simulator [38], using relative and absolute accuracies of 10^{-3} and 10^{-6} in algebraic equations system solving, and 10^{-6}, for both accuracies, for optimization variables and constraints violation. EMSO data on thermodynamic properties was also used.

For specific treated water cost (*spc*) calculation, Eqs. (1) and (2) were used.

$$spc = \frac{aCAPEX/f + OPEX}{V_{water}} \tag{1}$$

$$a = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{2}$$

In these equations, V_{water} is the annual recovered water volume, f is the plant utilization factor, i is the interest rate, n is investment period, *OPEX* are the operational expenditures, *CAPEX* are the capital expenditures and a is the amortization factor. Contingency, freight, insurance and other minor contributors were not considered explicitly due to their low relevance in the overall cost and similarity for all proposed routes.