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Application of ceramic membranes for water management in offshore oil production platforms: Process design and economics

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ABSTRACT

The application of the ceramic membrane separation processes are suitable for the generation of a treated effluent with high quality, enabling the reuse of the effluent and consequently reducing the emission of contaminants into the sea, the chemical consumption and the need to capture and treat seawater. Besides these advantages, membrane systems represent a reduction in weight and footprint, which are very limited on oil platforms. In this study, a technical analysis of an industrial unit to treat produced water was integrated with the seawater treatment system and carried out using data obtained from pilot scale tests, conducted with an industrial zirconia oxide ceramic membranes module, and from actual conventional systems operating data. Considering the integrated configuration, the additional investment cost was estimated at MUS$ 7.3 and it was possible to estimate that the extra cost would be recovered in about seven years, considering a unit capable of generating 1500 $m^3\ h^{-1}$ of treated effluent. This scenario represents a favorable condition for the application of ceramic membranes for oilfield produced water treatment on industrial units and its potential used on offshore oil production platforms.

1. Introduction

In offshore units large quantities of water need to be managed during oil production. Typically sea water is desalted by membrane separation processes and injected into the reservoir while the water, which is coproduced with oil and gas, is treated and disposed of into the sea. This stream, referred to as produced water, is a complex mixture of dispersed and dissolved components. The former includes dispersed oil and solids, while the latter can consist of water-soluble organic compounds, dissolved salts, and production chemicals [1]. These components need to have their levels reduced or completely removed so that oilfield produced water can be discarded at sea or reinjected into reservoirs, in order to increase oil recovery. In reservoirs with low permeability the water stream injected should have a concentration of oils and greases (O&G) of less than 5 mg L^{-1} [2] and a total of suspended solids less than 1 mg L^{-1} [3] in order to prevent an obstruction in the producing reservoir during the process of oil extraction [4]. However, the equipment commonly used in the treatment of oilfield produced water, such as hydrocyclones and dissolved gas flotators, are unable to remove suspended particles with particle sizes below 5.0 μm, as well as rarely obtain the water quality for reinjection in terms of the suspended solids and O&G content [3].

Beyond this difficulty, the increasing volume of waste all over the world in the current decade, the outcome and effect of discharging produced water into the environment has lately become a significant environmental concern issue [5], making it necessary to search for technologies which enable the reuse of the effluent in order to minimize these impacts. Note that for use in offshore oil production units, treatment systems must also be compact as a function of weight and space limitations on the platforms [6]. In this sense, the separation processes by ceramic membranes, considered unconventional in the oil industry, are a promising technology for the treatment of oilfield produced water on offshore platforms. Compared to conventional separation techniques, membrane technology offers easy implementation, considerable flexibility, compactness and good automation altogether with the decreasing installation and operation costs, makes membrane processes reliable, environmentally friendly, competitive and economically profitable alternative to other techniques [7–10]. Other advantages of ceramic membranes are related to the ability to treat oily waters without additional chemicals and its resistance against

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mechanical, thermal and chemical stress, allowing a better regeneration of the membrane with harsh chemical cleanings [11,12].

As shown in previous studies, the effluent produced from ceramic membrane treatment is adequate for reinjection [13,14]. Thus, the membrane separation process can contribute to reducing the consumption of chemicals products, as well as the need to collect and treat seawater, which is necessary to improve oil recovery. The seawater conventional treatment unit is generally comprised of a filtration system (media filters or cartridge filters), an oxygen removal system and a sulfate removal unit (SRU), which employs nanofiltration membranes [6].

Given the reported potential application of ceramic membranes for treating produced water, in conjunction with the need to use technologies that enable the effluents reuse on oil production platforms, the aim of this study was to evaluate the technical and economic feasibility for the oilfield produced water treatment by ceramic membrane unit integrated with the seawater desalting system used to enhance oil recovery. This innovative process configuration was compared to conventional units, taking into consideration the cost, weight and footprint required for the industrial installation of each configuration.

2. Materials and methods

2.1. Economic analysis of separation process membrane ceramics

2.1.1. General considerations

Most of the studies carried out so far referred to the application of ceramic membranes for oilfield produced water treatment were conducted in short-term experiments on lab scale units. Among the few long-term studies conducted on pilot scale units, the study presented by Weschenfelder et al. [15] was selected as a reference for the present study so that the technical analysis of the proposed configuration could be executed with permeate flux values which approached the conditions obtained in real industrial conditions.

Weschenfelder et al. [15] conducted experiments in continuous mode with zirconium oxide multi-channel membranes (0.1 μm pore size and 3.4 m^2 of permeation surface), which lasted 100 h, using synthetic oilfield produced water containing 100 mg L^{-1} of oil to supply the permeation unit. Operating conditions which were able to maximize the permeate flux were applied, i.e. transmembrane pressure (ΔP_{TM}) equal to 2.0 bar, cross flow velocity (V_{EC}) equal to 2.0 m s^{-1}, interval between air pulses in the permeate stream (IP) and backwashes (IB) equal to 5 min and 30 min, respectively. The membranes were chemically regenerated by a sequential application of alkaline solution (sodium hydroxide + sodium hypochlorite) and acid solution (citric acid) followed by washing with distilled water in order to eliminate the cleaning solution traces [15]. It was observed that the membranes regeneration every 100 h resulted in a lower total process cost. The reported results also showed that the treated effluent met the specification for reuse and the approximate value of the actual permeate flux (J_E) was 270 h^{-1} m^{-2}, for a water recovery rate of 80%. Similar results were obtained by Pedenaud et al. [16], who conducted tests on a pilot scale plant over 9 months with silicon carbide ceramic membranes (pore size of 0.04 m^2 and 10.2 m^2 of permeation surface area). Oilfield produced water (chloride content equal to 96,300 mg L^{-1}) coming from an onshore oilfield was continuously fed into the unit. To clean the membrane, alkaline and acid solutions and a low foaming detergent were used. The authors reported permeate fluxes in the range of 200–300 h^{-1} m^{-2}, considering V_{EC} in the range of 2.0–3.0 m s^{-1}, IB = 10 min and water recovery rate (R_A) = 90%.

Based on the results reported in the literature [15,16], an average effective permeate flux of 247 h^{-1} m^{-2} was adopted. For the analysis of the proposed configuration, operating conditions similar to those described in a previous study [15] were selected. Besides the literature information, for this paper it was also considered that the wastewaters generated by the chemical cleaning procedure could be integrated with other exhausted cleaning solutions in the platform and recycled to primary water/oil separation process (three phase separator). In this case, no additional costs were considered for the proposed process.

The reference for the oilfield produced water flow rate was obtained from the average of 10 different offshore fluid production curves. In general, there is a linear increase of produced water flow rate up to 10 years after the start of the oilfield exploration. After this period, the flow rate tends to remain constant at the maximum level. Taking this maximum value into account (1500 m^3 h^{-1}) and the seawater flow rate typically adopted for offshore projects (2000 m^3 h^{-1}), the proposed configuration was analyzed. Furthermore, for the ceramic membrane unit configuration several modules in parallel were considered. Each unit consists of housings containing ceramic membranes (modules), also arranged in parallel, with independent pumps and control systems. This consideration is conservative and may be optimized in the final version of an industrial system design. Additional information regarding the estimation of the ceramic membrane weight and footprint were obtained from suppliers and manufacturers, whereas for the conventional treatment unit corporate data belonging to an offshores oil production unit project were taken into account [17,18].

2.1.2. CAPEX

CAPEX, or capital expenditure, was determined by adding the costs of equipment, ceramic membranes, valves, piping and instruments that are part of the process [19,20]. The costs of the membranes and housing were estimated at US$ 520.00/m^2 and US$ 200.00/m^2, respectively, whereas the investment cost regarding peripherals such as valves, instruments, equipment and piping was estimated at US$ 780.00/m^2 [21]. The cost of the centrifugal pumps with a capacity of 3000 m^3 h^{-1} was estimated at US$ 126,000.00 [21]. The cost of the gas turbine which is very common in offshore oil production units, for the power supply, was estimated at US$ 1410 per installed kW [22].

2.1.3. OPEX

Values related to energy consumption, depreciation, replacement of the membrane, maintenance, labor and regeneration of the membrane were taken into account for operating expenses (OPEX) [19,23]. The energy required to operate the system (E_R) was calculated by Eq. (1). In this equation, E_R is related to the recirculation flow (Q), the pressure variation between the module's input and output (ΔP), the total membrane surface area (A) and pump efficiency (η) [19].

$$E_R = \frac{\Delta P \cdot Q}{A \cdot \eta} \quad (1)$$

The total membrane area was obtained by the ratio of the total flow of permeate arbitrated (1500 m^3 h^{-1}) and permeate effective flux obtained in the experiments. The energy cost was determined by multiplying E_R by the cost of the unit value of power generation (energy costs for offshore units was estimated at US$ 0.008 per kW h generated, considering the operating and maintenance costs related to gas turbines as well as the gas cost [24]) and by the time of operation, considering the pump efficiency as being at 80%.

A 10-year linear depreciation method was considered. This value was calculated by subtracting the membrane cost from the capital expenditure, divided by the period considered in the calculation. The membrane replacement cost depends on the type of membrane used and its lifetime. A 7-year membrane service life was considered for this analysis [23,25]. Guerra and Pellegrino [26] estimated the cost related to labor and maintenance in