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Energy requirements of the switchable polarity solvent forward osmosis (SPS-FO) water purification process

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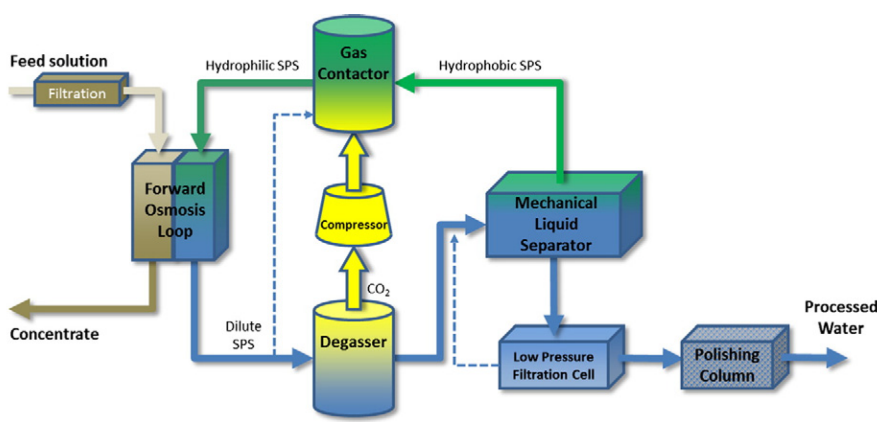
HIGHLIGHTS

- Concentration dependent SPS FO water treatment processes energy model.
- SPS FO process modeled with and without geothermal energy contributions.
- SPS FO found to be economically viable over a wide range of concentrations.

GRAPHICAL ABSTRACT



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ABSTRACT

A model was developed to estimate the process energy requirements of a switchable polarity solvent forward osmosis (SPS FO) system for water purification from aqueous NaCl feed solution concentrations ranging from 0.5 to 4.0 molal at an operational scale of 480 m^3/day (feed stream). The model indicates recovering approximately 90% of the water from a feed solution with NaCl concentration similar to seawater using SPS FO would have total equivalent energy requirements between 2.4 and 4.3 kWh per m^3 of purified water product. The process is predicted to be competitive with current costs for disposal/treatment of produced water from oil and gas drilling operations. Once scaled up the SPS FO process may be a thermally driven desalination process that can compete with the cost of seawater reverse osmosis.

1. Introduction

Previously our group introduced switchable polarity solvents (SPSs) [1–3] as a draw solution for forward osmosis (FO) [4]. The SPS FO process has the potential to treat very high concentration solutions; the process has already been demonstrated to provide positive FO flux against a NaCl solution at 5 molal or 226,000 ppm total dissolved solids (TDS) [4]. As a thermally driven process SPS FO may be a more cost effective than electrically driven processes, such as reverse osmosis (RO), even if more energy is required. Heat energy is approximately a tenth the cost of electricity per unit energy so even with a lower energy efficiency SPS FO is expected to have a low cost. FO also offers potential for reduced fouling issues and pretreatment requirements when

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compared to RO. Pretreatment costs are often 60% of the cost to treat oil and gas water with RO versus the core hydraulic RO energy requirements contributing only ~20% of the total treatment cost. The SPS FO system also has the potential to be driven by low-grade heat source which can be obtained at great discount in the form of waste heat from an industrial process.

The SPS class of solvents is capable of switching between an aprotic non-ionic form, to a water soluble ionic solute through the introduction and removal of CO_2 (Eq. (1)).

$$NR_{3(org)} + CO_{2(g)} + H_2O \rightleftharpoons HNR^{+}_{3(aq)} + HCO^{-}_{3(aq)} \quad (1)$$

The ionic form can act as a draw solute in an FO process and then be separated from the product water through the application of heat; the heat driving off carbon dioxide and generating the water-immiscible aprotic tertiary amine. SPS is an example of a growing number of switchable thermolytic and thermal sensitive solutes [5–14]. Our initial demonstration of the SPS FO process used dimethylcyclohexylamine (DMCA) [4]. While DMCA is a potential SPS draw solute an SPS optimized for SPS FO process has been sought [15–18] and suggest 1-cyclohexylpiperidine is an especially promising candidate. Regardless of the SPS employed in the process DMCA is an excellent model SPS and was used to develop the process energy model.

While SPS FO appears promising in terms of energy requirements and process costs, a rigorous evaluation had not been conducted. In the following text, a process model is developed to estimate the SPS FO process energy requirements and capital and operating costs similar to work done during the development of the ammonia–CO_2 draw system [19]. This model was a prerequisite for pursuing the SPS FO concept further and will be used to guide the integration and development of scale demonstrations and pilot systems.

The model was used to investigate two potential applications for SPS FO technology: desalination and treatment of produced waters from oil and gas drilling operations. While there is some variation in the range of temperature and salinity values typical of seawater desalination feed streams, these variables can vary considerably for produced water treatment applications. Produced water generally exits oil and gas wells at temperatures greater than ambient. The salinity of produced water may vary from levels similar to that of drinking water to several times more saline than sea water [20]. The process model was implemented to analyze the effect of feed water stream temperature and composition on process energy requirements and product yield.

Since SPS FO process thermal energy requirements can be met using low grade heat, an elevated temperature produced water feed stream could be utilized as the heat source for supplying SPS FO process thermal energy demands. Depending on the feed water stream temperature, several different SPS FO process heat integration schemes could be utilized. Three scenarios, each with different heat integration schemes, were investigated to evaluate the energy requirements and costs associated with processing feed water streams supplied over a range of temperatures. Scenario 1 is applicable for situations where the feed water stream is supplied at temperatures similar to ambient such that thermal energy input to meet process heat demands must be provided by an external heat source. Scenario 2 is applicable when the feed water stream is supplied at a temperature sufficient to provide the process thermal energy input. Scenario 3 is applicable in situations where the feed stream temperature is sufficiently high to provide heat input to an organic Rankine cycle (ORC) power cycle in addition to SPS FO process thermal energy input.

2. Process model and assumptions

A basic process flow diagram of the SPS FO process is provided in Fig. 1. An Aspen Plus process flow diagram with the major process components from the basic process flow diagram highlighted is included as Fig. 2. Non-highlighted items include compressor/pumps, heat exchangers, valves, etc. required to adjust the process conditions of the flow in and out of the major components. Many of the process energy requirements are associated with the ancillary process components that function in support of the major components.

The SPS FO process simulation was performed using a feed water stream volumetric flow rate basis of 20 m^3/h. The feed water stream pressure was set to a value equal to that of the concentrated draw stream exiting the gas contactor such that there is no hydraulic pressure differential across the FO membrane. The feed water stream was simulated as an aqueous NaCl stream with concentration ranging from 0.5 to 4.0 molal (28,400–189,500 ppm TDS), which brackets the feed water salinity typical of most desalination and produced water treatment applications. The feed water stream temperatures evaluated in this analysis vary according to the assumptions of each of the three scenarios evaluated.

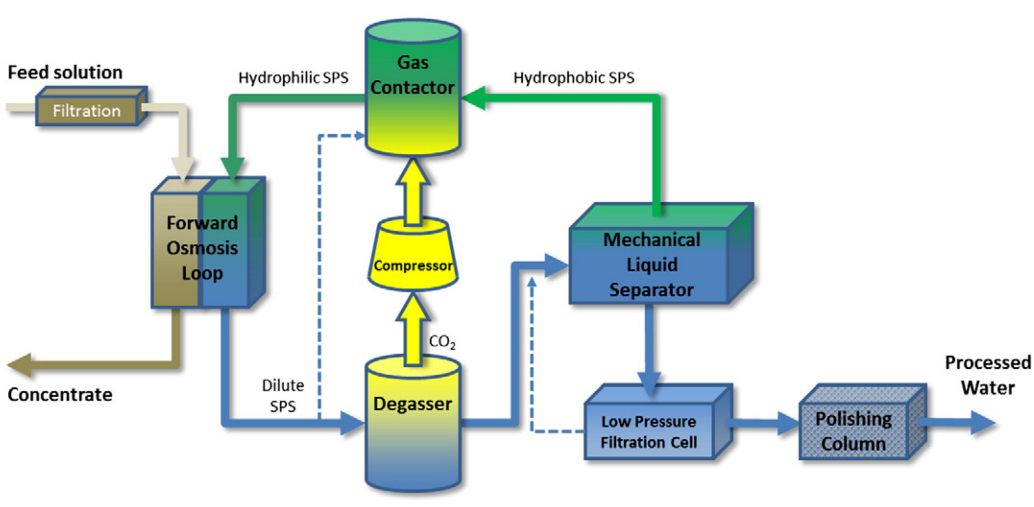

Fig. 1. The proposed switchable polarity solvent forward osmosis (SPS FO) process.