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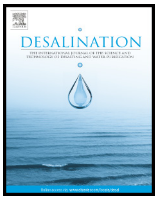

Treatment of basal water using a hybrid electrodialysis reversal–reverse osmosis system combined with a low-temperature crystallizer for near-zero liquid discharge

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HIGHLIGHTS

- This pilot study investigated the use of ZLD approach to treat basal aquifer water.
- Pretreatment through sedimentation and UF proved to be effective in removing solids.
- The hybrid EDR–RO desalination system achieved about 77% recoveries.
- The evaporator-crystallizer was able to concentrate the EDR–RO brine.
- The system was effective to produce freshwater and minimize brine discharge.

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ABSTRACT

Basal aquifer water is saline groundwater that often needs to be dewatered prior to mining. The oil sands industry is seeking cost-effective methods to treat basal aquifer water in order to allow its recycle to the bitumen extraction process. A hybrid desalination system consisting of advanced electrodialysis reversal (EDR)–reverse osmosis (RO) combined with a low-temperature evaporator/crystallizer was assessed as an opportunity to treat basal aquifer water for a near-zero liquid discharge (ZLD) approach. The pilot-scale plant had a capacity of 50 m^3/day influent. Pretreatment through sedimentation and ultrafiltration proved to be effective in removing both suspended solids and turbidity. The hybrid EDR–RO desalination system achieved about 77% recoveries, with brine concentrations up to 125,000 mg/L. The results showed that the evaporator-crystallizer was able to concentrate the EDR–RO brine to a conductivity of just over 250 mS/cm, while producing additional freshwater. This proof-of-concept study demonstrated that the hybrid EDR–RO system combined with a low-temperature evaporator/crystallizer was an effective near-zero ZLD approach to produce freshwater and minimize brine discharge when treating basal aquifer water.

1. Introduction

There are over 168 billion barrels of recoverable crude bitumen available in the Athabasca oil sands deposits, making Canada the country with the third largest oil reserves in the world [1]. Depending on the depth of the deposit, crude bitumen can be recovered economically by open-pit mining when it occurs near the surface or by using in situ methods when the crude bitumen is found at greater depths. In situ recovery takes place both by primary development, similar to conventional crude oil production, and by enhanced development methods such as cyclic steam stimulation (CSS) and steam-assisted gravity drainage (SAGD). When operating oil sands by open-pit mining, overburden is removed, oil sands ore is mined, and bitumen is extracted from the mined material using hot water. As the overburden and bitumen deposits are removed, the underlying basal aquifer water becomes depressurized, flooding the open mine pit. Dewatering wells have been installed to minimize the upwelling of the basal water to the mine pit. The basal aquifer water is characterized by high salinity and hardness [2,3]. Currently, the dewatered basal water is stored in ponds until it is successfully remediated and reclaimed.

With increased development of the oil sands resource, the oil sands companies have recently focused on reducing their freshwater usage by seeking new water sources. Treating basal aquifer water using efficient and cost-effective methods to remove organic and inorganic components will allow recycling it to process bitumen and reducing the need for freshwater resources. Very few studies have investigated the possibility of treating basal aquifer water. The desalination of basal water was assessed using electrodialysis (ED) [3]. In order to achieve effective ED treatment, basal water was pretreated with coagulation–flocculation–sedimentation (CFS) to remove solid species and turbidity. The results showed that ED was effective in decreasing the conductivity of basal water by 99% and in removing ionic species by an average of 93–97%, depending on the membrane stack type.

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Desalination by using reverse osmosis (RO) membranes has become very popular for producing freshwater from brackish water and seawater [4]. However, membrane lifetime and permeate fluxes are primarily affected by fouling (e.g., microbial adhesion, gel-layer formation, and solute adhesion) at the membrane surface [5]. Electrodialysis (ED) and electrodialysis reversal (EDR), membrane-based techniques used to transport salt ions from one solution through ion-exchange membranes to another solution under the influence of an applied electric potential difference, have also been used for water desalination [6,7]. Recently, the use of hybrid ED–RO (or EDR–RO) has been found to be suitable not only for the desalination of surface and groundwater [8], but also for better brine management [9]. By designing a hybrid process, the RO process can supply the concentrated brine as the high salinity feed solution for the EDR (or ED), while EDR can be used as a pretreatment of the RO feed solution, resulting in the reduction of the osmotic pressure of the RO feed solution [9,10].

Previously, ED on RO concentrate has been successfully used to reduce the volume of salty water discharge and to improve the overall water recovery [11]. Turek et al. [12] reported overall water recovery of 91.6% when using an RO–EDR system to treat the brackish water. Similarly, Oren et al. [10] found improvement of water recovery by using an RO–EDR process with a side loop crystallizer to treat brackish groundwater, achieving overall water recovery of 98%. This proof-of-concept pilot-scale study was conducted to assess the ability of an advanced EDR–RO hybrid desalination system followed by a low-temperature evaporator/crystallizer to economically treat basal aquifer water for a near-zero liquid discharge (ZLD). Producing freshwater and minimizing brine discharge were the main goals of this study. Because effective pretreatment strategies are needed to prevent membrane fouling and to extend the lifetime of the RO membranes [13], the pilot-scale plant included the use of sedimentation, microfiltration (MF), and ultrafiltration (UF) as pretreatment steps. The impact of the different pretreatment steps on the water quality of the basal water was also examined. To determine the potential effects of the EDR membrane performance when operated in basal aquifer water over time, a stack duration test was also conducted.

2. Materials and methods

2.1. Basal aquifer water

The pilot testing was conducted at Saltworks Technologies Inc. in Vancouver, British Columbia, Canada. Representative samples of McMurray basal aquifer water from the Canadian Natural Horizon Mine were received in three shipments of 40,000 L between October 2012 and February 2013. The water samples were stored in 10,000 L fully contained tanks. During the storage period, the basal water was aerated and circulated among the tanks to prevent anaerobic conditions due to the presence of hydrocarbons in the basal aquifer water. During the tests, the basal water temperature was 17 ± 2 °C.

2.2. Pilot plant

The pilot plant used for the treatment of basal aquifer water consisted of a sedimentation tank for particle settling; 50 μm microfiltration (SWCH — HXP BF-1-2; membrane area of 1.5 m^2 per bag filter) for the filtration of micro-sized suspended solids; UF (SWUF — HM250; membrane area of 125 m^2 per module) for the filtration of submicron suspended solids; EDR (ElectroChem™ patented by Saltworks Technologies Inc.) to soften the water prior to feeding the RO unit and to concentrate the brine reject from the RO unit; RO (Hydranautics SWC5-LD; membrane area of 37.1 m^2 per element) to produce freshwater; and a low-temperature evaporator/crystallizer (SaltMaker™ patented by Saltworks Technologies Inc.) to treat the brine discharge from the EDR–RO hybrid system in order to produce more freshwater and solid salts. The plant had a capacity of 50 m^3/day influent. Fig. 1 shows a diagram of the treatment train used in this pilot study.

The EDR system consisted of three hydraulic streams (Fig. S1 in the Supplementary material): (i) the pretreated basal aquifer stream to be softened (product compartment “P” tank); (ii) intermediary stream that allowed an increase in concentration (transfer compartment “D” tank); and (iii) a final salt acceptor stream (concentrate compartment “C” tank). The RO brine reject flowed into this compartment (“C” tank), which was further concentrated.

During the plant operation, the EDR unit “pumped” ions around the RO feed (Point E in Fig. S1) and into the system brine reject (Points M, N, and P) to increase the system recovery and reliability through reduced RO inorganic fouling potential without the need for chemical softening. The EDR and RO units were fed from a common buffer header (“P” tank). The EDR desalted the RO feed in a closed hydraulic loop. The RO brine was recirculated to the “P” tank approximately 95% of the time (Point G) with periodic blowdown (Point H) to the brine circuit to purge the RO feed of non-ionic species. Ion species fluxed internal to the EDR stack from a low concentration feed (Point I to J desalted) into moderate concentration salt transfer solution (Point K to L transfer) and then into the high concentration brine discharge (Point M to N concentrated). The transfer solution was employed since the salt concentration across any single ion exchange membrane compartment was limited to approximately 75,000 mg/L, due largely to membrane concentration polarization. RO permeate (Point F) left the system as a desalted product (freshwater), while the EDR–RO brine (Point P) was sent to the low-temperature evaporator/crystallizer. The crystallizer produced concentrated brine or solids (Point S) and freshwater (Point R).

Conventional chemical pretreatments such as lime softening and ion exchange were not employed in this pilot study. The pilot plant incorporated full automated operation, including start/stop, and self-cleaning/flushing. For the EDR system, the self-cleaning was performed by reversing the polarity of the electrodes, while for the RO membranes, acid cleaning was performed to manage the membrane fouling. All key operating parameters, such as conductivities, pH, pressures, flow rates, temperatures, were logged with a data acquisition (DAQ) system.

3. Results and discussions

3.1. Water chemistry of basal aquifer water

A summary of key water quality parameters of untreated basal aquifer water fed to the pilot plant is presented in Table 1. Basal water had slightly elevated pH (8.41) and low turbidity content (3.0 NTU). The levels of total suspended solids (TSS) and total dissolved solids (TDS) of the basal water samples were 10 mg/L and 25,100 mg/L, respectively. Due to the high degree of variability throughout the North Athabasca Oil Sands area resulting from the natural hydrogeologic complexity, typically the TDS of the McMurray formation waters (i.e., groundwater) vary from non-saline (<240 mg/L) to brine (279,000 mg/L) [14].

Basal water had significantly higher levels of sodium (8770 mg/L) and chloride salts (14,000 mg/L), and contained a high level of alkalinity (2420 mg/L as $CaCO_3$). These findings agreed with previous publication [3]. The results also showed that other salts predominantly associated with scaling of membrane water treatment systems, namely sulfates, calcium, magnesium, barium, and strontium were also present in the basal water (Table 1).

Organic compounds were key consideration in this pilot study as they have the potential to foul membrane systems, resulting in performance reductions [15–17]. TOC levels of 34 mg/L were recorded for untreated basal water, with naphthenic acid (NA) concentration of 6.6 mg/L. It is noteworthy that NAs, a mixture of alicyclic and alkyl-substituted aliphatic carboxylic acids, are environmental concerns due to their toxicity to fish [18] and benthic invertebrates [19], among other organisms. NAs are present naturally in crude oils and they comprise part of the petroleum acids. Typically, oil sands crude oils contain

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