ENERGY REQUIREMENT OF ALTERNATIVE TECHNOLOGIES FOR DESALINATING GROUNDWATER FOR IRRIGATION

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Abstract

Increased global water demand coupled with limited water resources has led to acute water shortage in many regions, significantly affecting agriculture, which is the world's largest consumer of water. Groundwater resources are thus increasingly being used to meet irrigation requirements. However, groundwater resources around the world tend to be saline ($0.5 \leq S \leq 5$ g/kg) requiring desalination before use. Furthermore, with decreasing water availability, demands for producing permeate from the feed at higher recoveries (>85%) is also increasing. In this work, a thermodynamic least work analysis for desalination and pumping ground water is developed first. Then, the actual energy required by high recovery desalination technologies such as brackish water reverse osmosis (RO), closed circuit reverse osmosis (CCRO) and electrodialysis reversal (EDR) are compared with the thermodynamic least work of desalination from 50-95% recovery. CCRO consumed the least energy until a recovery of 92% after which EDR consumed the least energy. While the energy required for RO and CCRO changed with recovery, EDR energy consumption remained approximately constant at 0.85 kWh/m^3. Water table depth was also found to significantly contribute to the total energy consumed, with the power required to pump groundwater being comparable to the desalination power requirements at water table depths greater than 50 m. Thus, the choice of selection of desalination technologies is particularly crucial for water table depths less than 50 m.

I. INTRODUCTION

There are 1.43 billion hectares of cropland world, of which only 257 million hectares (18%) are irrigated [1]. Although studies have shown that irrigation increases crop yield over rain-fed agriculture by over 50%, water availability, water quality, and economic factors often limit the expansion of irrigation systems [2]. As freshwater sources become depleted, groundwater is looked to as a potential source for irrigation water. In addition to the issue of cost for both the required well and pumping system [1], groundwater quality often does not meet crop requirements [3]. Over half of the groundwater in the world is brackish ($0.5 \leq S \leq 5$ g/kg) [4]. Irrigating with high salinity water can damage the soil and decrease crop yield, an effect that is estimated to have caused the reduction in productivity of approximately 20-30 million hectares of irrigated land [4]. Solutions that would allow for cost effective, high recovery, desalination of brackish groundwater are desired. This paper considers the energetic benefits of two high recovery technologies, closed circuit reverse osmosis (CCRO) and electrodialysis reversal (EDR), and compares them to standard brackish water reverse osmosis (RO).

II. METHODOLOGY

Four different desalination cases were modeled: the thermodynamic least work, EDR, RO, and CCRO. Thermodynamic analyses of typical brackish water compositions confirmed that feed and brine streams could be approximated as aqueous sodium chloride solutions. The feed salinity was assumed to be 3 g/kg while the product salinity was assumed to be 0.2 g/kg. The system operating temperature was 20°C. Permeate recoveries of 50-95% were simulated for each case and the power consumed per product flow rate (i.e., specific energy) was obtained.

2.1 Least work for desalination and pumping

The least specific work required to both pump water up from a groundwater well and complete the desalination process is given in Eq. 1 where the first term on the right hand side represents the specific energy for pumping and the second term represents the least specific energy of separation required to extract a unit of water from a feed stream of a given salinity for any black-box separator [5]

$$E_{\mathrm{spec,least}} = \frac{\alpha g h \rho_{\mathrm{f}}}{\eta_{\mathrm{p}} R} + \left[g_{\mathrm{p}} + \left(\frac{1}{R} - 1\right) g_{\mathrm{b}} - \left(\frac{1}{R}\right) g_{\mathrm{f}}\right] \tag{1}$$

where $E_{\mathrm{spec,least}}$ is the least specific work, R is the recovery ratio, $g_{\mathrm{p}}, g_{\mathrm{b}}, g_{\mathrm{f}}$ are the specific Gibbs free energies of the permeate, brine, and feed stream, g is the acceleration due to gravity, ρ_{f} is the density of the feed stream, η_{p} is the pump efficiency (set to 0.80), α is a factor accounting for friction losses [6] and h is the water table depth, approximated here as the lift of the pump. α was set to 1.18 so that the pump work was 0.004 kWh/m^3-m, a mean field value reported by Plappally and Lienhard [7]. The Gibbs free energy of aqueous sodium chloride was obtained from Robinson and Stokes [8].

2.2 Electrodialysis

An EDR system was simulated by modifying the model previously derived by Ortiz et al. [9] for application to a continuous (steady state) system. The stack modeled has 170 total cell pairs dividing into two electrical stages, each having two hydraulic stages. Each membrane has an effective membrane area of 0.32 m^2. All parameters for this stack are taken directly from the membrane and stack documentation available from GE [10]. The production rate of the system is 1.6 m^3/hr. The specific energy consumption of any EDR plant is highly dependent on the stack arrangement and size. Increasing available membrane area leads to an increase in the capital cost of the system and a decrease in energy consumption. The stack chosen for this model is the smallest available industrial EDR stack offered by GE Water capable of meeting the feed and product water requirements for this comparison. The model thus represents a form of upper limit on the energy consumption for this feed water concentration.

2.3 Reverse osmosis

A multi-stage fixed inlet pressure reverse osmosis (RO) system without pressure recovery was simulated by modifying an analytical thermodynamic model previously used by Mistry et al. [5]. Osmotic coefficient data for aqueous sodium chloride from Robinson and Stokes [8] was correlated and used to calculate osmotic pressure. A system pinch pressure of 5 bar (between hydraulic and osmotic pressure) and a pump efficiency of 70% was assumed based on literature data [11]. The number of stages was increased to meet the required recovery with the individual recovery in each stage being 45%.

2.4 Closed circuit reverse osmosis

CCRO is a type of batch RO process consisting of a single-stage RO unit, a high pressure pump and a circulation pump that allows for high recoveries to be obtained [12,13] . Desalination occurs in batches with the brine being recirculated back as feed with the feed-side pressure ramped up in each batch to overcome the increased osmotic pressure. Detailed operational data from CCRO field units operating at 88% recovery for feed salinities of 2.5 g/kg has been reported in literature alongside published claims of 97% recovery being achieved as well [11]. In this work, the CCRO process was simulated using an analytical thermodynamic model similar to that used by Mistry et al. [5]. A module recovery of 45%, a batch pressure loss of 1 bar, a minimum driving pressure difference of 5 bar and pump efficiencies of 70% were assumed based on field data [11,14]. The model was verified against the recovery and power consumption data reported by Stover [13]. The model matched the data to within 6.5%.

III. RESULTS

3.1 Least work for desalination and pumping

Figure 1 shows the relationship between feed water salinity, water table depth, and least specific work for well pumping and desalination (kWh/m^3). It is included here for the purposes of comparison to the specific energies of RO, CCRO and EDR. For water table depths greater than 50 m, the energy required for pumping is of the same order as that required for the desalination process.

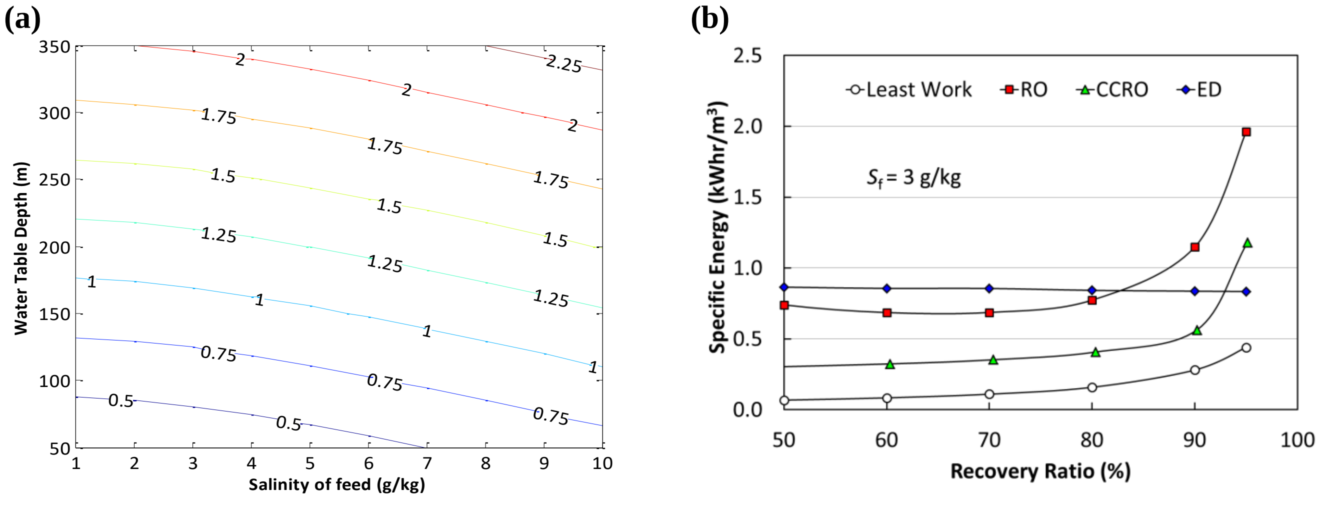

Figure 1. (a) Variation of least work (in kWh/m^3) for pumping and desalination with feed salinity and water table depth. **(b)** Variation of specific energy consumption with recovery ratio for the least work for desalination (without water table pump), RO, CCRO and EDR for a feed salinity, S_f = 3 g/kg.

3.2 Comparison of specific energy with recovery

CCRO consumed the least amount of energy until a recovery of 92% after which EDR consumed the least energy. For recoveries up to 90%, CCRO energy consumption was within 0.25 kWh/m^3 of the least work for desalination. EDR energy consumption did not vary much with recovery averaging 0.85 kWh/m^3 — a characteristic relevant for water sources where feed salinity varies across a wide range. For recoveries up to 82%, EDR consumed the most energy, more than even single-stage RO. However, the energy consumption for RO increased substantially after 82%. Furthermore, single-stage RO would require several membrane modules to deliver high recovery, drastically increasing capital costs.

IV. CONCLUSIONS

In this work we first analyzed the specific energy requirement to pump water from the water table to the surface, followed by the specific energy requirements of RO, CCRO, and EDR at varying recovery ratios. For recoveries less than 92%, CCRO consumed the least energy, with the specific energy consumption varying 0.20-0.83 kWh/m^3. Above 92% recovery, EDR consumed the least energy at 0.83 kWh/m^3. For water table depths greater than 50 m, the energy required for pumping is comparable to that required for the desalination process. For water table depths less than 50 m, selection of an appropriate desalination technology becomes more crucial. It is recommended that further work be conducted in this area, especially analysis work on system capital cost and overall system performance under different feed water concentrations.

V. REFERENCES

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