HYBRIDIZATION OF HUMIDIFICATION-DEHUMIDIFICATION AND PRESSURE RETARDED OSMOSIS FOR BRINE CONCENTRATION APPLICATIONS

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Abstract

A novel hybridization of brine-recirculating humidification-dehumidification (HDH) desalination with pressure retarded osmosis (PRO) is proposed and analyzed. Because HDH operates at low recoveries in a single pass, brine recirculation is required to achieve the high recovery ratios required for brine concentration applications like oil and gas produced water treatment. The mixing of the recirculated brine stream with lower salinity feed destroys exergy, which can be recovered with PRO. Results show that because of the low single pass recovery inherent to HDH, the high salinities encountered in brine concentration, and the elevated temperature of the brine stream, the hybridized PRO unit can operate near optimal conditions for maximum power production. We show that for a reversible PRO system, a maximum of about 10 kWh/m^3-product can be generated. For an irreversible system, we estimate about 2.7 kWh/m^3-product can be produced under typical feed and brine salinities—more than enough to power HDH auxiliaries and take the system completely off grid. The recovered exergy is equivalent to a second-law efficiency that is between 1% and 7% higher than standalone HDH, depending on feed water characteristics and the performance of the HDH and PRO subsystems.

I. INTRODUCTION

A novel hybrid of humidification-dehumidification (HDH) desalination and pressure retarded osmosis is proposed to produce clean water and power in brine concentration applications. In brine concentration applications, HDH is generally configured in a manner that recirculates a portion of the brine produced in a single evaporative pass so that greater recoveries of product (fresh) water can be achieved from the feed stream. When a portion of this very saline brine is mixed with incoming feed, large irreversibilities are generated. The exergy destroyed in this mixing process can be instead recovered in a pressure retarded osmosis system, producing electrical power, which could be used to drive auxiliary equipment and eliminate the need for onsite power generation in off-grid areas such as oil and gas drilling sites.

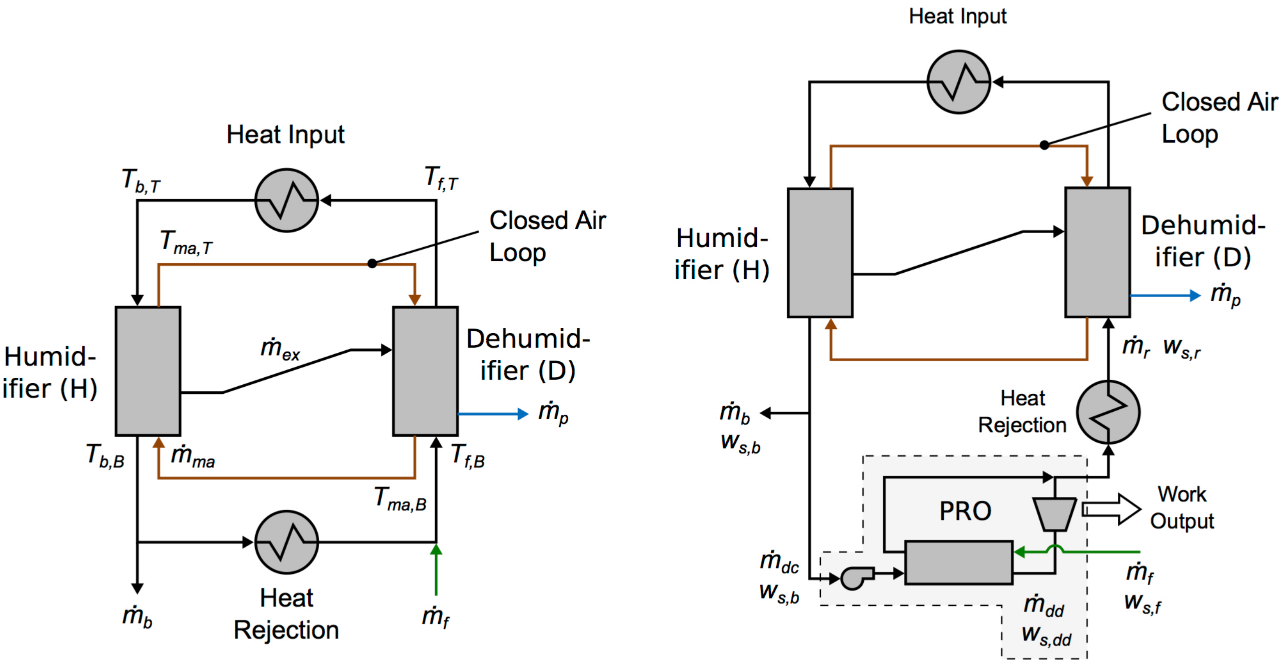
PRO has previously been investigated in hybrid configurations with seawater desalination systems, but found to be of limited use [1,2]. PRO has also more recently been investigated in tandem with forward osmosis for both power production and water treatment by mixing a hyper-saline hydraulic fracturing wastewater stream with a more dilute wastewater effluent [3]. The two key distinguishing factors in the present novel configuration are: (1) the brine concentration application, and (2) the low recovery inherent in single pass HDH. Generally, PRO is most effective (i.e., it produces the most power per unit feed) when the draw salinity is both high relative to the feed and high in absolute terms, where the slope of the osmotic pressure versus salinity curve is higher. Furthermore, with PRO before the heat rejection step, the osmotic pressure of the brine will be higher than at room temperature, which increases the possible power output and can reduce the size of the heat exchanger required in the heat rejection step. In brine concentration HDH, the absolute value of salinity is high, the ratio between recirculated brine and feed salinity is high, and the brine stream is warm. This combination means that the PRO system is operating over its most effective domain.

II. PROCESS DESCRIPTION

Humidification-dehumidification, shown schematically in Fig. 1a is a desalination process that uses air as a carrier gas to evaporate water from a saline feed stream. Several cycle variants exist [4], but we restrict the analysis to the closed-air, closed-water system (CACW), which sufficiently characterizes the systems used in brine concentration applications. In the humidifier, a warm feed humidifies a cool, dry air stream in counterflow. The warm, moist air exits the humidifier and is cooled and dehumidified in the dehumidifier, producing a pure water condensate ($\dot{m}_p$). The cooled air is recirculated in a closed loop. Exchanging a portion of the air or water streams at a midpoint ($\dot{m}_{ex}$) can improve cycle performance [5–8]; this is known as extraction and injection. A portion of the concentrated brine exits the system ($\dot{m}_b$) and the remainder is cooled and mixed with the incoming feed ($\dot{m}_f$).

In PRO, a concentrated draw and feed stream are separated by a semi-permeable membrane in counterflow. The semi-permeable membrane selectively admits water but rejects dissolved salts. The difference in osmotic pressure on either side of the membrane causes a flow of pure water from the feed stream into the pre-pressurized draw. This increases the volumetric flow rate of the pressurized draw stream, which can be depressurized in a turbine to produce electrical work.

In the closed water, or brine recirculation variant of HDH, a portion of the concentrated brine from the humidifier is recirculated, cooled, and mixed with the feed. This technique—essential in brine concentration applications—is used to achieve higher recovery ratios ($\mathrm{RR} = \dot{m}_p/\dot{m}_f$) than are obtainable in a single pass HDH arrangement. However, as the brine and feed streams are mixed, exergy is destroyed. The proposed humidification-dehumidification pressure retarded osmosis hybrid (HDH-PRO), shown schematically in Fig. 1b, instead recovers the irreversibility lost in the mixing process and generates useful electrical work. The recirculated brine stream ($\dot{m}_{dc}$) is fed through a PRO membrane unit, where it is diluted and pressurized by the feed stream ($\dot{m}_f$). The diluted draw ($\dot{m}_{dd}$) stream is then depressurized in a turbine, which produces power. The depressurized, diluted draw stream is then mixed with the concentrated feed and fed to the HDH system. In an ideal case, both the concentrated feed and diluted draw would be at the same salinity.



(a) Traditional HDH **(b) HDH-PRO Hybrid**

Fig. 1: Schematic diagrams of a traditional, single-extraction brine recirculation HDH system and the novel hybridized HDH-PRO variant. In a traditional, closed water HDH system (a), a portion of the brine is recirculated and mixed with the feed to achieve high recovery ratios. In the HDH-PRO hybrid (b), the recirculated stream is pressurized and then diluted in a mass exchanger, increasing its volume flow and providing a net work output.

III. PROCESS ANALYSIS

In this section, we will discuss the relevant parameters that define the performance of the HDH-PRO hybrid and estimate its performance. An upper bound on the performance of the system will be defined by an analysis of a reversible PRO system, and more typical values of power production will be estimated using the ε-MTU model [9–11] for mass exchanger rating. In the subsequent analyses, we focus on the case of desalinating high salinity produced water as an illustrative example. We approximate this case as follows: (1) the saline streams are modeled as pure aqueous NaCl, using thermophysical properties from Pitzer [12]; (2) the brine salinity is fixed at $w_{s,b} = 26\%$; and (3) the feed salinity $w_{s,f}$ is varied from zero to the brine salinity. A detailed justification of these approximations is given in [13].

The parametric space that defines the best operating performance of HDH-PRO is characterized by three interrelated variables: RR, the single pass recovery ratio of the HDH subsystem (SPR $= \dot{m}_p/\dot{m}_r$), and the mass flow rate ratio of the PRO subsystem ($\mathrm{MR} = \dot{m}_{dc}/\dot{m}_f$). PRO produces the greatest amount of work when mass flow rate ratios are high, i.e., ≥4. The value of MR is dictated by the recovery ratio in a single pass of the HDH system, SPR, and the recovery ratio of the entire system, RR. From a salt balance on the shaded PRO control volume in Fig. 1b, the MR is

$$\mathrm{MR} = \frac{\mathrm{RR-SPR}}{\mathrm{SPR}} \tag{1}$$

which is shown in Fig. 2. Thus, we see that the PRO subsystem will perform best when the hybrid system is operating at RR above 25–50%, depending on the SPR of the HDH subsystem. These values are typical recoveries for oil and gas produced water brine concentration, indicating that the hybridization is well matched to the technical application.

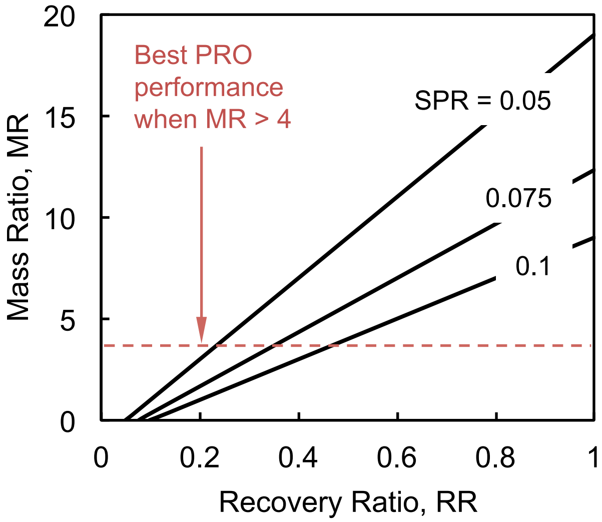


Fig. 2: PRO operates best at mass ratios above about 4, which occurs when it is hybridized with typical HDH systems operating at RR above 25–50%, depending on the SPR, which are representative of values in brine concentration applications.

3.1 Reversible Process Analysis

A salinity gradient engine (SGE), such as pressure retarded osmosis, converts the exergy between two streams of dissimilar salinity into electrical work. The amount of work produced by a reversible SGE provides an upper bound on the potential work recovered from the HDH-PRO hybridization. Combining the First and Second Laws of Thermodynamics as applied to the shaded control volume in Fig. 1b yields the following expression in the reversible case:

$$\frac{\dot{W}_{\mathrm{rev}}}{\dot{m}_p/\rho_p} = \frac{\rho_p}{\mathrm{RR}}\left[\mathrm{MR}(g_{dc} - g_r) + g_f - g_r\right] \tag{2}$$

where g is the Gibbs free energy, and the subscripts *dc*, *r*, and *f* denote the concentrated draw, recirculated, and feed streams, respectively. We have written the reversible work per unit product water of the HDH system ($\dot{m}_p$) so that the numbers can easily be compared to the exergy requirements of the desalination (HDH) process, which are normalized in the same fashion.

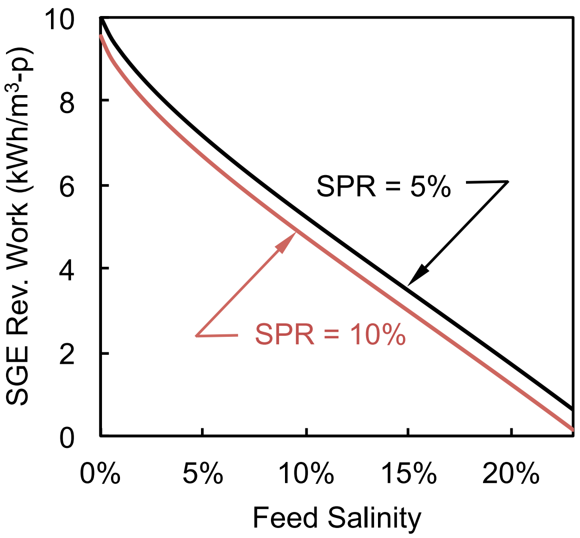


Fig. 3: For a typical HDH system with SPR between 5% and 10% and typical produced water feed salinities between 5% and 20%, a reversible salinity gradient engine (SGE) can recover between 1 to 7 kWh per m^3 of product water.

Noting that $\mathrm{RR} = 1 - w_{s,f}/w_{s,b}$, for the fixed $w_{s,b}$ = 26%, the reversible work can be computed as a function of $w_{s,f}$ and the SPR. As shown in Fig. 3, a maximum of about 10 kWh/m^3 is achievable at low feed salinities (high RR), when a large portion of brine is recirculated. The upper bound on recoverable work reduces by about 0.1 kWh/m^3 per percent increase in SPR.

3.2 Irreversible Process Analysis

The maximum power of a real, irreversible PRO system is obtained when the system size is large and the MR is above about four[1]. From [11], under these conditions, the work per unit feed is

$$\frac{\dot{W}}{\dot{m}_f} = \frac{\eta_t}{\rho_{dd}}\left(\sqrt{\pi_d} - \sqrt{\pi_f}\right)^2 \tag{3}$$

where π denotes osmotic pressure, ρ_{dd} is the density of the dilute draw, and η_t is the combined efficiency of the turbine and generator. Additional approximations required to derive Eq. 3 include a linear relationship between osmotic pressure and salinity (van ‘t Hoff relation), no internal or external concentration polarization, a constant membrane water permeability, and no hydraulic pressure losses in the exchanger. As work is usually normalized per unit product in a desalination system, and we wish to benchmark this power production against work requirements for desalination systems, we plot $\dot{W}/\dot{m}_p = \dot{W}/\dot{m}_f(1/RR)$ in Fig. 4. For typical brine concentration applications like shale gas produced water with a feed salinity of 15% and a 25°C brine stream, a work output of 2.66 kWh/m^3 can be produced with a large PRO system. This energy increases by about 8% per 10 °C increase in brine stream temperature. For a typical, small-scale installation of 1000 m^3 of product per day, this equates to

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[1] For high feed salinities (low recovery), the MR is below 4. However, for large system sizes (i.e., for large number of mass transfer units [11]) Eq. (3) only overpredicts the work at lower MR by about 10\%.

about 110 kW. The total electrical consumption of HDH is reported to be about 0.45 kWh/m^3 [7], indicating that even capturing 17% of the power from a large PRO unit would be sufficient to power the HDH auxiliaries and make the system completely grid independent.

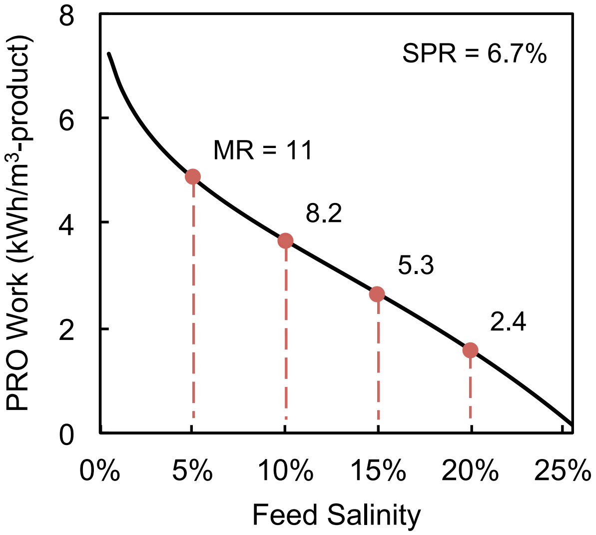

Fig. 4: The potential for HDH-PRO – the system can produce nearly 3 kWh/m^3 in a large system at typical produced water feed salinities.

IV. EFFECTIVE EFFICIENCY GAIN

By reducing the net exergy input to the desalination system, the hybridization of PRO with the closed water HDH system effectively increases the efficiency of the system. The efficiency of the combined system is

$$\eta_{\mathrm{HDH-PRO}} = \frac{\dot{W}_{rev}}{\dot{W}_{act}} = \frac{\dot{W}_{rev}/\dot{m}_p}{(1-T_{f,B}/T_{b,T})\mathrm{GOR}/h_{fg}-\dot{W}_{PRO}/\dot{m}_f\mathrm{RR}} \quad (4)$$

where $\dot{W}_{rev}/\dot{m}_p$ is the work required to drive a reversible HDH system [14] and $\dot{W}_{act}/\dot{m}_p$ is the actual exergetic input to the hybrid system. The reversible work is not a function of the hybridization, as the states of all HDH inlet and outlet streams with and without the PRO hybridization are identical.

The difference in efficiency between the hybrid HDH-PRO system and standalone HDH will depend on the performance of the HDH and PRO subsystems. Choosing typical values of SPR = 6.7%, $T_{b,T} = 70°\mathrm{C}$, and η_t = 95%, efficiencies between 1% and 7% higher than standalone HDH are achievable by hybridizing with a large, irreversible PRO system, as shown in Fig. 5. At higher GOR, we observe greater efficiency gains because the exergy recovered by the PRO system is more comparable to the exergetic input to the heater in the HDH cycle. At low feed salinities (high RR), the least work is low, and the reduction in exergy input is small compared to that required to drive the HDH system. Conversely, at high salinities (low RR), less brine is recirculated, which corresponds to a lower MR—and work output—of the PRO system. Consequently, the highest gains in efficiency appear at feed salinities between 10% and 15%, where the two effects are balanced: significant brine recirculation, but a small enough exergy input to the HDH system's heater.

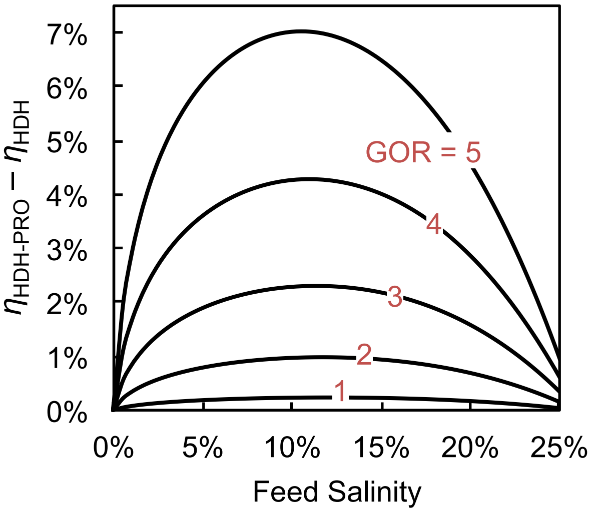

Fig. 5: For a typical HDH system with SPR = 6.7% and $T_{b,T}$ = 70°C, hybridization with PRO results in efficiencies about 1%–7% higher than standalone HDH, depending on the GOR of the HDH subsystem and its feed salinity.

V. CONCLUSIONS

In this work, the feasibility of hybridizing humidification dehumidification desalination with pressure retarded osmosis has been analyzed. We have shown that the hybridization is particularly well matched in brine concentration applications, where the low single-pass recovery inherent to HDH results in the coupled PRO unit operating at near optimal conditions for maximum power output. We estimate that for a somewhat typical unconventional oil and gas produced water stream at 15% feed salinity and 26% brine salinity, the reversible limit of power production is about 3.3 kWh/m^3-product. A large, irreversible system could produce nearly 2.66 kWh/m^3-product. The analysis showed the hybridization results in efficiencies about 1% and 7% higher than standalone HDH, depending on the GOR of the HDH subsystem and the feed salinity. The excess power produced would be more than enough to take the desalination system completely off grid, and could be used to power other non-desalination related auxiliaries at the treatment site.

ACKNOWLEDGMENTS

The authors would like to thank the King Fahd University of Petroleum and Minerals for funding the research reported in this paper through the Center for Clean Water and Clean Energy at MIT and KFUPM under project numbers R4-CW-08 and R13-CW-10. LDB acknowledges that this material is based upon work supported by the National Science Foundation Graduate Research Fellowship Program under Grant No. 1122374.

VI. REFERENCES

1. L. D. Banchik and J. H. Lienhard V, "Thermodynamic analysis of a reverse osmosis desalination system using forward osmosis for energy recovery," in *ASME 2012 International Mechanical Engineering Congress and Exposition*, American Society of Mechanical Engineers, 2012.
2. W. Akram, M. H. Sharqawy and J. H. Lienhard V, "Energy utilization of brine from an MSF desalination plant by pressure retarded osmosis," in *The International Desalination Association World Congress on Desalination and Water Reuse 2013, Tianjin, China*, 2013.
3. A. Altaee and N. Hilal, "Dual-stage forward osmosis/pressure retarded osmosis process for hypersaline solutions and fracking wastewater treatment," *Desalination*, vol. 350, pp. 79 – 85, 2014.
4. G. P. Narayan, M. H. Sharqawy, E. K. Summers, J. H. Lienhard V, S. M. Zubair, and M. A. Antar, "The potential of solar-driven humidification-dehumidification desalination for small-scale decentralized water production," *Renewable and Sustainable Energy Reviews*, vol. 14, pp. 1187–1201, May 2010.
5. G. P. Narayan, K. Chehayeb, R. K. McGovern, G. P. Thiel, S. M. Zubair, and J. H. Lienhard V, "Thermodynamic balancing of the humidification dehumidification desalination system by mass extraction and injection," *International Journal of Heat and Mass Transfer*, vol. 57, pp. 756–770, 2013.
6. G. P. Thiel and J. H. Lienhard V, "Entropy generation in condensation in the presence of high concentrations of noncondensable gases," *International Journal of Heat and Mass Transfer*, vol. 55, pp. 5133–5147, September 2012.
7. G. P. Narayan, M. St. John, S. M. Zubair, and J. H. Lienhard V, "Thermal design of the humidification-dehumidification desalination system: an experimental investigation," *International Journal of Heat and Mass Transfer*, vol. 58, pp. 740–748, 2013.
8. G. P. Thiel, J. A. Miller, and J. H. Lienhard V, "Effect of mass extractions and injections on the performance of a fixed-size humidification-dehumidification desalination system," *Desalination*, vol. 314, pp. 50–58, 2013.
9. M. H. Sharqawy, L. D. Banchik, and J. H. Lienhard V, "Effectiveness-Mass Transfer Units ε-MTU Model of an Ideal Pressure Retarded Osmosis Membrane Mass Exchanger," *Journal of Membrane Science*, vol. 445, pp. 211–219, 2013.
10. L. D. Banchik, M. H. Sharqawy, and J. H. Lienhard V, "Effectiveness-Mass Transfer Units Model of an Ideal Reverse Osmosis Membrane Mass Exchanger (ε-MTU)," *Journal of Membrane Science*, vol. 458, pp. 189–198, 2014.
11. L. D. Banchik, M. H. Sharqawy, and J. H. Lienhard V, "Limits of power production due to finite membrane area in pressure retarded osmosis," *Journal of Membrane Science*, vol. 468, pp. 81–89, 2014.
12. K. S. Pitzer, J. C. Peiper, and R. H. Busey, "Thermodynamic properties of aqueous sodium chloride solutions," *Journal of Physical and Chemical Reference Data*, vol. 13, pp. 1–102, 1984.
13. G. P. Thiel, E. W. Tow, L. D. Banchik, H. Chung, and J. H. Lienhard V, "Energy consumption in desalinating produced water from shale oil and gas extraction," *Desalination*, 2015.
14. K. H. Mistry and J. H. Lienhard V, "Generalized least energy of separation for desalination and other chemical separation processes," *Entropy*, vol. 15, pp. 2046–2080, May 2013.