Environmental Science & Technology

Viewpoint

pubs.acs.org/est

Energy Consumption by Recirculation: A Missing Parameter When Evaluating Forward Osmosis

Shiqiang Zou,[†] Heyang Yuan,[†] Amy Childress,[*,‡] and Zhen He[*,†]

[†]Department of Civil and Environmental Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061, United States

[‡]Sonny Astani Department of Civil and Environmental Engineering, University of Southern California, Los Angeles, California 90089, United States

INTRODUCTION

Membrane-based water reclamation technologies have demonstrated great potential to address the water-energy nexus. Among these technologies, forward osmosis (FO) can contribute to the recovery of high-quality water by taking advantage of osmotic pressure gradient across a semipermeable membrane. The major applications of the FO process lie in two realms. The first pertains to systems where FO essentially serves as high-quality pretreatment for a downstream desalination process (e.g., a reverse osmosis (RO) or distillation process), which reconcentrates the draw solution and provides high-quality product water. The second realm pertains to systems that do not require a reconcentration process, including osmotic concentration of complex feed solutions for volume reduction (e.g., domestic and industrial wastewater, landfill leachate and digester effluent) and osmotic dilution of application-specific draw solutes (e.g., fertilizers). FO offers operation with low or no hydraulic pressure requirements, high rejection of undesired compounds, and reversible fouling with prolonged membrane lifespan. Significant efforts have been invested in developing specialized membranes to enhance water flux and reduce solute leakage and in designing efficient methods to reconcentrate the draw solution. As some of the technical barriers have been overcome, commercial FO systems are being piloted in a growing number of applications where low energy consumption is a priority.

ENERGY CONSUMPTION IN FORWARD OSMOSIS SYSTEMS

FO has been widely referred to as an "energy-efficient" process or an energy-efficient pretreatment process for a subsequent desalination process (e.g., RO or distillation); however, energy consumption data have rarely been reported in the literature.[1] The possible energy consumers in the FO process include: pretreatment of the feed and draw solutions, recirculation pump(s), draw solution reconcentration, fouling control, and post-treatment of the concentrated feed solution. In most cases, physical backwashing can be used to achieve at least 90% performance recovery from fouling with low energy input (though lacking quantitative data in the literature). It is expected that 71−98% of the total energy, quantified as the specific energy consumption (SEC, kWh per m^3 reclaimed water), is required for the solute reconcentration process. An early study of a hybrid FO-RO system estimated an SEC of 25 kWh m^{-3}, with 76% (19 kWh m^{-3}) being consumed by solute reconcentration (i.e., RO).[2] In another study, the energy-intensive RO process was eliminated by using an NH_3-CO_2 draw solution that was thermally reconcentrated using waste heat. This resulted in a significant SEC reduction for the whole system (0.84 kWh m^{-3}), with 71% (0.60 kWh m^{-3}) attributed to reconcentration;[3] in this case, 29% (0.24 kWh m^{-3}) was required for recirculation pumps. From this study, a threshold value of 0.25 kWh m^{-3} was later used by many studies addressing energy-related issues in FO systems excluding solute reconcentration. Furthermore, it was observed that in systems that required reconcentration, recirculation energy accounted for approximately 25−30% of the total demand. This significant percentage is not a surprise given that bench-scale FO systems are typically operated using flow rates ranging from 400 to 1000 mL min^{-1} (8.5−21.3 cm s^{-1} in a 1.0-cm pipe), and that pilot-scale systems operate at even higher flow rates. It is clear that as FO systems are tested at larger scales, the cost of recirculation can become one of the decisive factors in FO competitiveness.

RECIRCULATION PUMPS: THE BLIND SPOT

As an essential part of an FO system, the recirculation pumps not only transfer well-mixed solutions to the membrane, they also provide hydraulic shear forces to minimize external

Received: June 7, 2016
Published: June 23, 2016

DOI: 10.1021/acs.est.6b02849
Environ. Sci. Technol. 2016, 50, 6827−6829

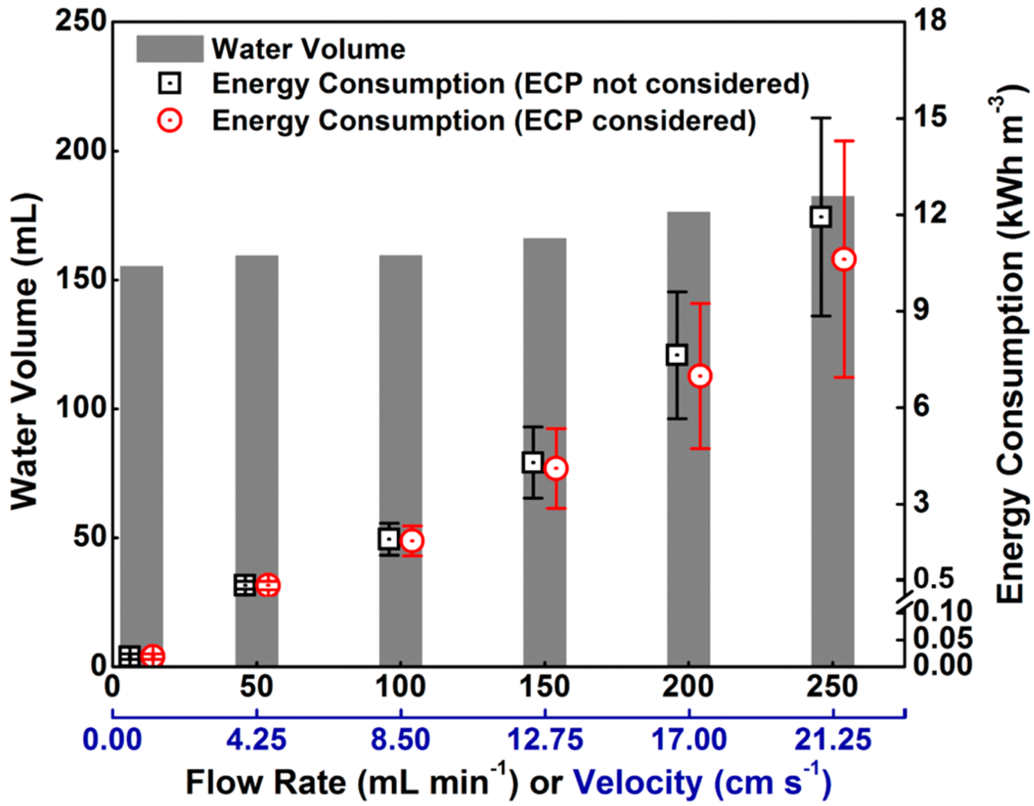

Figure 1. SEC and recovered water volume under different flow rates or velocities in a submerged FO operated for 24 h using the treated wastewater as the feed and 1-M commercial fertilizer solution as the draw. The data at the recirculation flow rate of 0−100 mL min^{-1} were obtained from a previous study[4] with permission.

concentration polarization (ECP) and fouling. However, very few studies (less than five publications since 2005) have reported the energy consumption of recirculation pumps, and the majority of those have not shown detailed calculations. In a recent study that has quantified the SEC associated with recirculation pumps, FO is used to reclaim wastewater for the dilution of solid fertilizer in agricultural applications.[4] In this scenario, reconcentration is not required and essentially all of the energy consumed is for recirculation. Under a flow rate of 10 mL min^{-1} (0.85 cm s^{-1}, 0.5 cm tubing), the FO system reclaimed 155 mL of water in 24 h, rendering an SEC of 0.02 ± 0.01 kWh m^{-3} (Figure 1). The estimated SEC (11.93 ± 3.08 kWh m^{-3}) for a flow rate of 250 mL min^{-1} (21.25 cm s^{-1}) was higher. Improvement to mass transfer with higher flow rates was limited (water recovery of 182 at 250 mL min^{-1}) due to the negligible ECP at relatively low water fluxes. It was estimated that a minimum SEC of 1.86 ± 0.47 and 11.93 ± 3.08 kWh m^{-3} would be required in this FO system for flow velocities of 8.50 and 21.25 cm s^{-1} (which are typical values reported in the FO studies), respectively.

■ IMPLICATION OF RECIRCULATION ENERGY

The power required by a recirculation pump is determined by flow rate and hydraulic head loss (which is related to the diameter of the tubing)[5] and thus the data presented here are only examples and may not represent energy consumption by FO systems with different configurations/operation. However, the data indicate that the high flow rates used in many laboratory-scale studies may need to be reconsidered in light of the energy required for recirculation. Although water flux may be enhanced with a higher recirculation rate in some FO systems and/or under different operating conditions, the resulting increased energy demand must be considered. Furthermore, to truly realize the energy efficiency of FO, lower flow rates may be favored. This has significant implication for the design of next-generation FO membranes; current research emphasizes the design of membranes with high water permeability to achieve high fluxes. Additional research is needed to prioritize high selectivity (low salt permeability) over productivity in order to improve not only energy efficiency but also overall process efficiency. Furthermore, improved reporting of energy consumption for bench-, pilot-, and demonstration-scale studies would enable better understanding of the competing challenges toward optimizing the process and advancing FO commercialization.

■ AUTHOR INFORMATION

Corresponding Authors

*(A.C.) Phone: (213) 740-6304; e-mail: amyec@usc.edu.
*(Z.H) Phone: (540) 231-1346; e-mail: zhenhe@vt.edu.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was financially supported by a grant from National Science Foundation (#1358145).

■ REFERENCES

(1) Shaffer, D. L.; Werber, J. R.; Jaramillo, H.; Lin, S.; Elimelech, M. Forward osmosis: Where are we now? *Desalination* **2015**, *356*, 271−284.

DOI: 10.1021/acs.est.6b02849
Environ. Sci. Technol. 2016, 50, 6827−6829

(2) Cath, T. Y.; Gormly, S.; Beaudry, E. G.; Flynn, M. T.; Adams, V. D.; Childress, A. E. Membrane contactor processes for wastewater reclamation in space: Part I. Direct osmotic concentration as pretreatment for reverse osmosis. *J. Membr. Sci.* **2005**, *257* (1), 85−98.
(3) McGinnis, R. L.; Elimelech, M. Energy requirements of ammonia-carbon dioxide forward osmosis desalination. *Desalination* **2007**, *207* (1), 370−382.
(4) Zou, S.; He, Z. Enhancing wastewater reuse by forward osmosis with self-diluted commercial fertilizers as draw solutes. *Water Res.* **2016**, *99*, 235−243.
(5) Kim, J.; Kim, K.; Ye, H.; Lee, E.; Shin, C.; McCarty, P. L.; Bae, J. Anaerobic Fluidized Bed Membrane Bioreactor for Wastewater Treatment. *Environ. Sci. Technol.* **2011**, *45* (2), 576−581.

DOI: 10.1021/acs.est.6b02849
Environ. Sci. Technol. 2016, 50, 6827−6829