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Multi-objective Optimization of Solar-driven, Hollow-fiber Membrane Distillation Systems

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Abstract

Securing additional water sources remains a primary concern for arid regions in both the developed and developing world. Climate change is causing fluctuations in the frequency and duration of precipitation, which can be can be seen as prolonged droughts in some arid areas. Droughts decrease the reliability of surface water supplies, which forces communities to find alternate primary water sources. In many cases, ground water can supplement the use of surface supplies during periods of drought, reducing the need for above-ground storage without sacrificing reliability objectives. Unfortunately, accessible ground waters are often brackish, requiring desalination prior to use, and underdeveloped infrastructure and inconsistent electrical grid access can create obstacles to groundwater desalination in developing regions. The objectives of the proposed project are to (i) mathematically simulate the operation of hollow fiber membrane distillation systems and (ii) optimize system design for off-grid treatment of brackish water. It is anticipated that methods developed here can be used to supply potable water at many off-grid locations in semi-arid regions including parts of the Navajo Reservation. This research is a collaborative project between Sandia and the University of Arizona.

ACKNOWLEDGMENTS

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1. INTRODUCTION

Worldwide, over 2.7 billion people are impacted by water scarcity.[1] Population growth and climate change may increase that number to over five billion by 2025.[2] Many drought-stricken areas also have high poverty rates, which makes coping with water shortages especially challenging with far-reaching consequences. However, the possibility of access to seawater or brackish ground water makes desalination a feasible alternative for mitigating drought. Desalination is energy intensive and therefore a relatively expensive process. As a large fraction of impoverished communities are remote and not electrified, energy requirements must be met without access to a centralized power grid. Solar-driven desalination technologies are highly appropriate for mitigating water scarcity under these circumstances. One example is membrane distillation (MD), a thermal process in which the energy required for desalination is provided as solar thermal energy, rather than photovoltaic (PV) energy. Under some circumstances, this provides substantial cost savings over pressure-driven systems.

2. RESULTS AND DISCUSSION

A non-steady process model was developed to simulate a sweeping gas membrane distillation system powered by solar thermal and photovoltaic power for the desalination of drinking water. The cost of water is estimated from manufacturer-provided equipment costs and various economic heuristics. Multi-variable optimization is performed in MATLAB to minimize the cost of water. The average annual operating cost is about $4,500. Fixed expenses are the largest fraction of operating cost, followed by membrane replacement costs. Additionally, analysis of partial derivative of the cost with respect to each decision variable indicates that the number of membrane modules and thermal collector area have the largest effect on the amortized cost of water. This, combined with the fact that they make up the largest fraction of the equipment cost, indicate that future work in membrane distillation must be focused on improving the economics of these two pieces of equipment in particular.

The optimized cost reported here exceeds most previously reported costs.[3,4] Many previous studies neglect important cost considerations, such as miscellaneous capital expenses or the cost of electricity. While the cost calculated in this study is higher, it represents a more accurate accounting of costs associated with solar driven membrane distillation. However, some equipment used in this study can be further optimized to lower costs. Therefore, further work is needed in the modeling and optimization of compact membranes specialized for membranes distillation.

The optimization algorithm selects the values of decision variables in an optimized system. Most notably, the hot water tank selected is the smallest permitted by the algorithm, indicating that the thermal energy storage associated with a larger hot water tank is uneconomical. Several other decision variables, including the photovoltaic collector area, flow rates, and operating period configuration, are selected to minimize battery use suggesting that neither thermal nor electrical energy storage leads to economy in solar-driven SGMD water purification. This solution and accompanying analysis provides general guidance related to the cost of water purification via SGMD and the sensitivity of those costs to equipment-related and operational decision variables.

3. CONCLUSION

The model and methods presented can be used to estimate the effects of design constraints and the impact of geographic variables on the cost of water purification by solar SGMD. Major equipment costs inform recommendations regarding improvements necessary to make this technology economically competitive. Additional work is necessary to illustrate the effect of the water production constraint (economies of scale) and discount operator on optimization results.

The model can be used to optimize membrane characteristics such as pore size, tortuosity, and module dimensions rather than to optimize the process as presented here. This will help inform the development of membranes specialized for membrane distillation.

The details of this research can be found in references 5 and 6:

5) Moore, S.E.; Mirchandani, S.; Karanikola, V.; Nenoff, T.M.; Arnold, R.G.; Sáez, A.E. "Process modeling for economic optimization of a solar driven sweeping gas membrane distillation desalination system" *Desalination*, **2017**, submitted.

6) Moore, S. E., S. Mirchandani, V. Karanikola, T. M. Nenoff, R. G. Arnold, A. E. Saez. "Optimization of a solar driven membrane distillation system for cost and efficiency." *Desalination*, **2017**, in preparation.

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4) Khayet, M., 2013. Solar desalination by membrane distillation: Dispersion in energy consumption analysis and water production costs (a review). *Desalination,* Volume 308, pp. 89-101.

5) Moore, S.E.; Mirchandani, S.; Karanikola, V.; Nenoff, T.M.; Arnold, R.G.; Sáez, A.E. "Process modeling for economic optimization of a solar driven sweeping gas membrane distillation desalination system" *Desalination*, **2017**, submitted.

6) Moore, S. E., S. Mirchandani, V. Karanikola, T. M. Nenoff, R. G. Arnold, A. E. Saez. "Optimization of a solar driven membrane distillation system for cost and efficiency." *Desalination*, **2017**, in prep.

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