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Techno-economic assessment of a closed-loop osmotic heat engine

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ABSTRACT

Osmotic power harnesses the energy of mixing between high salinity and low salinity streams to generate mechanical energy. The closed-loop osmotic heat engine (OHE) is a low-grade heat powered, membrane-based energy system that couples membrane distillation (MD), a thermally driven membrane process, with pressure retarded osmosis (PRO), an osmotically driven membrane process. The objective of this study was to evaluate the technical and economic feasibility of an OHE to generate electricity. Experimental data and previously established MD and PRO models were used to develop an OHE system model that calculates system efficiency (a ratio between the net energy output and thermal energy input), net power output, and electricity generation costs. Results show that the levelized cost of electricity generation by an OHE at the current state of the technology is $0.48 per kWh, which is not competitive with wholesale conventional U.S. grid electricity costs of $0.04/kWh [1], nor comparable to low-grade heat-powered Organic Rankine Cycle electricity generation costs ($0.08–0.13/kWh). To investigate the robustness of the OHE model, a sensitivity analysis was performed to evaluate the influence of select model inputs on electricity costs. Results indicate that improving PRO membrane power density has the highest potential benefit to reduce OHE electricity generation costs. Development of highly permeable and selective PRO membranes that are mechanically stable at increased hydraulic pressures is critical for maturation of PRO and OHE. Alternative working fluids capable of producing higher osmotic pressures and having lower reverse solute fluxes may aid in increasing OHE performance, but not substantially. Our analysis shows that substantial improvements to system operation and membrane performance could reduce electricity generation cost of large installations close to $0.10 per kWh.

1. Introduction

While alternative and renewable energy technologies that focus on reducing the dependence on fossil fuels often attract attention, increasing the energy efficiency of existing industrial processes has the potential to significantly reduce fossil fuel consumption [2]. Industrial processes consume nearly 30% of the U.S. energy supply, and 20–50% of the energy consumed is lost in the form of low-grade heat (LGH) [2]. For example, conventional coal-fired power plants have an average efficiency of 32%, leaving a large fraction of unused heat to be potentially recovered [3]. Reports published by the U.S. Department of Energy estimate that approximately 60% of the emitted heat is of low-quality, and at temperatures less than 230 °C [2,4,5]. Existing commercial technologies that can recover useful energy from LGH sources include the Organic Rankine Cycle (ORC), which operates commercially with a temperature input of between 90 °C and 300 °C [2,6–8]. However, large amounts of waste heat in the range of 45 °C to 60 °C are produced in industrial plants [9] and remain largely unrecovered, thus representing a significant opportunity to implement technologies that can economically utilize lower temperature resources. Therefore, the purpose of this study was to evaluate the technical viability of one such technology—the osmotic heat engine (OHE).

The OHE is a closed-loop, membrane-based energy cycle that converts thermal energy into osmotic pressure to produce electrical energy [10,11]. The system analyzed in this study couples membrane distillation (MD), a thermally driven membrane process with pressure-retarded osmosis (PRO), an osmotically driven membrane process (Fig. 1). In the OHE, MD utilizes LGH to separate diluted brine into two streams: deionized water and high concentration brine. The two streams are then transferred into the PRO process, where the osmotic pressure difference between the streams, separated by a semipermeable membrane, is converted into mechanical energy that can be further

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Symbols

A_m	*membrane area [m^2]*
A_{hx}	*heat exchanger area [m^2]*
a	*amortization factor*
C	*concentration [g^{-1}]*
FP	*footprint [m^2]*
HC	*high concentration*
H	*pressure head [m]*
i	*inflation rate [%]*
J_s	*salt flux [g m^{-2} h^{-1}]*
$J_{w,MD}$	MD water flux [L m^{-2} h^{-1}]
J_w	PRO water flux [L m^{-2} h^{-1}]
l	*element length [m]*
LC	*low concentration*
M	*mass [kg]*
n	*plant lifetime [yr]*
N	*number of membrane elements*
P	*pressure [kPa]*
PA	*plant availability [%]*
PD	*power density [W m^{-2}]*
Q	*flow [L h^{-1}]*
r	*membrane element radius [m]*
R	*recovery [%]*
S	*specific costs [\$ kWh^{-1}]*
U	heating duty [kW]
u	*overall heat transfer coefficient [kW]*
V	*volume [m^3]*
W	*power [kW]*
η	*efficiency [%]*
λ	*membrane replacement rate*

Subscripts

b	*bleed*
e	*element*
f/d	*feed or d*
h	*high concentration*
hx	*heat exchanger*
i	*inlet*
l	*low concentration*
m	*membrane*
MD	*membrane distillation*
o	*outlet*
p	*permeate*
PRO	*pressure retarded osmosis*
px	*pressure exchanger*
r	*recycle*
t	*tank*
tg	*turbine generator*
v	*vessel*

converted into electrical energy via a turbine-generator set. The diluted brine from the PRO process is then reconcentrated in the MD process. Operating PRO within a closed-loop configuration offers several benefits over open-loop configurations, including control of solution chemistry and temperature, and avoiding pretreatment of the feed stream. Controlled solution chemistry also enables the use of high purity working fluids and eliminates membrane fouling and scaling, thereby reducing environmental emissions associated with membrane cleaning [10,12–20].

To determine the techno-economic viability of the OHE process, a system model was developed to evaluate the net energy and system efficiency (a ratio between net energy output and thermal energy input) for a 2.5 MW (net power) system. The system size is based on the average size of commercially available small-scale ORC plants [8], with ORC being one of a few commercially available technologies that can utilize LGH for electricity generation. For the purpose of the current study, ORC was considered a benchmark technology. Outputs from the system model were used to determine the capital and operation and maintenance (O & M) costs associated with constructing and operating the OHE plant. Using the generated costs, the levelized cost of electricity generation was calculated, assuming a twenty-year plant life.

The paper is organized in three sections, including a review of prior research that has looked at the component technologies used in the OHE, an overview of the modeling approach for the components and the OHE system, and lastly a discussion of the results from model analysis and directions for future research.

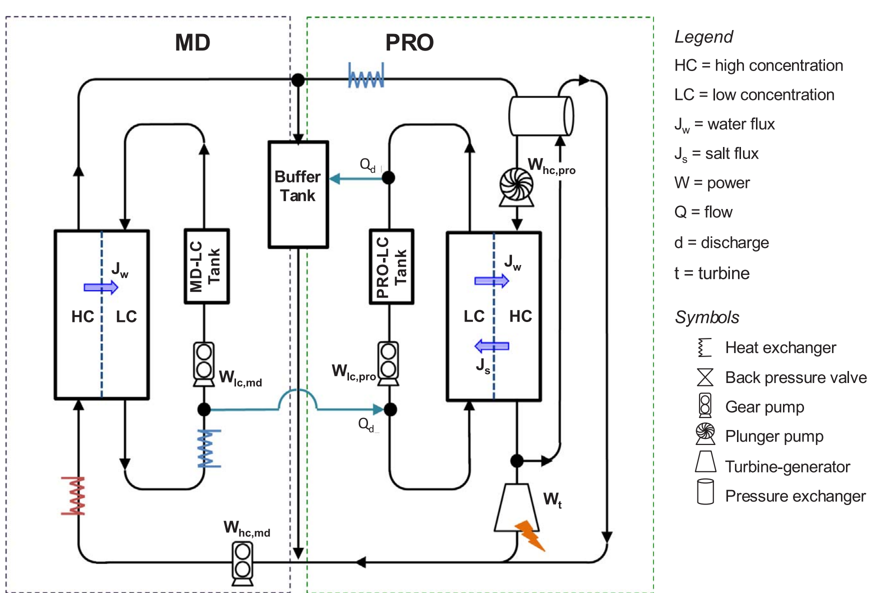

Fig. 1. Schematic of the closed-loop OHE. The thin blue arrows represent the portion of the PRO feed stream discharged to the MD feed stream for recovery of solutes and control of PRO feed chemistry. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)