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Comparative life-cycle assessment of a novel osmotic heat engine and an organic Rankine cycle for energy production from low-grade heat

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ABSTRACT

A comparative life-cycle assessment (LCA) was performed to evaluate the environmental impacts of an osmotic heat engine (OHE) and an organic Rankine cycle (ORC) for electrical energy generation from low-grade heat. The OHE is a novel membrane-based process that couples pressure retarded osmosis (an energy generating process) and membrane distillation (a working fluid regeneration process), whereas the ORC is an established power cycle. The LCA considered the material use for system construction and operation, and found that the environmental impacts for both the construction and operation stages of the OHE were higher than the ORC. The sensitivity analysis concluded that OHE environmental impacts could be reduced by 80% with future improvements to PRO membranes and membrane module performance. Additionally, with further improvements the OHE could be a viable energy production process that can increase energy efficiency and reduce CO_2 emissions from coal and natural gas power plants by 20.5 and 11.9 million kg of CO_2 per year, respectively.

1. Introduction

Development of renewable energy production technologies that maximize efficiency and minimize resource consumption is necessary to protect the environment and secure energy resources for future generations. Fossil fuel-based energy has been identified as the main source of anthropogenic greenhouse gas (GHG) emissions (Raluy et al., 2005a, 2005b). However, GHG contributors such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) can be reduced by implementing low carbon energy technologies and increasing energy efficiency in existing power plants and industrial processes (IPCC, 2007; EPA, 2012). Thermal inefficiencies in conventional power plants and industrial processes exist in the form of low-grade heat (LGH)—an abundant and largely underutilized energy source (EPA, 2012). Although several technologies have been developed and investigated for utilization of LGH, the organic Rankine cycle (ORC) is one of the only commercially available technologies that can utilize LGH to generate electrical energy (EPA, 2012; DOE, 2008). The ORC is similar to a steam cycle, but in place of water, an organic working fluid is used. The benefits of using an organic working fluid include lowered risk of condensation in the expander (i.e., turbine) and lower working temperatures; however, organic working fluids are typically toxic, less chemically stable, flammable, and can have high global warming and ozone depletion potential (Quoilin et al., 2013; Saleh et al., 2007; He et al., 2012; Bai, 2012; Liu et al., 2013; Tchanche et al., 2011). Additionally, the ORC is limited to operating at temperatures higher than 90 °C (Quoilin et al., 2013; Saleh et al., 2007).

The osmotic heat engine (OHE) is a hybrid, closed-loop membrane-based system that utilizes low-temperature (>50 °C) LGH and salinity gradient energy to produce electrical energy (Fig. 1) (Hickenbottom et al., 2016a; McGinnis et al., 2007). In the OHE, pressure retarded osmosis (PRO), an osmotically driven membrane process, is coupled with membrane distillation (MD), a thermally driven membrane process, or with other thermal separation processes. In PRO, water permeates via osmosis through a semi-permeable membrane from a low concentration feed stream into a higher concentration brine (draw solution). The permeate stream becomes pressurized on the high concentration side of the membrane and a mechanical/electrical device (e.g., turbine generator

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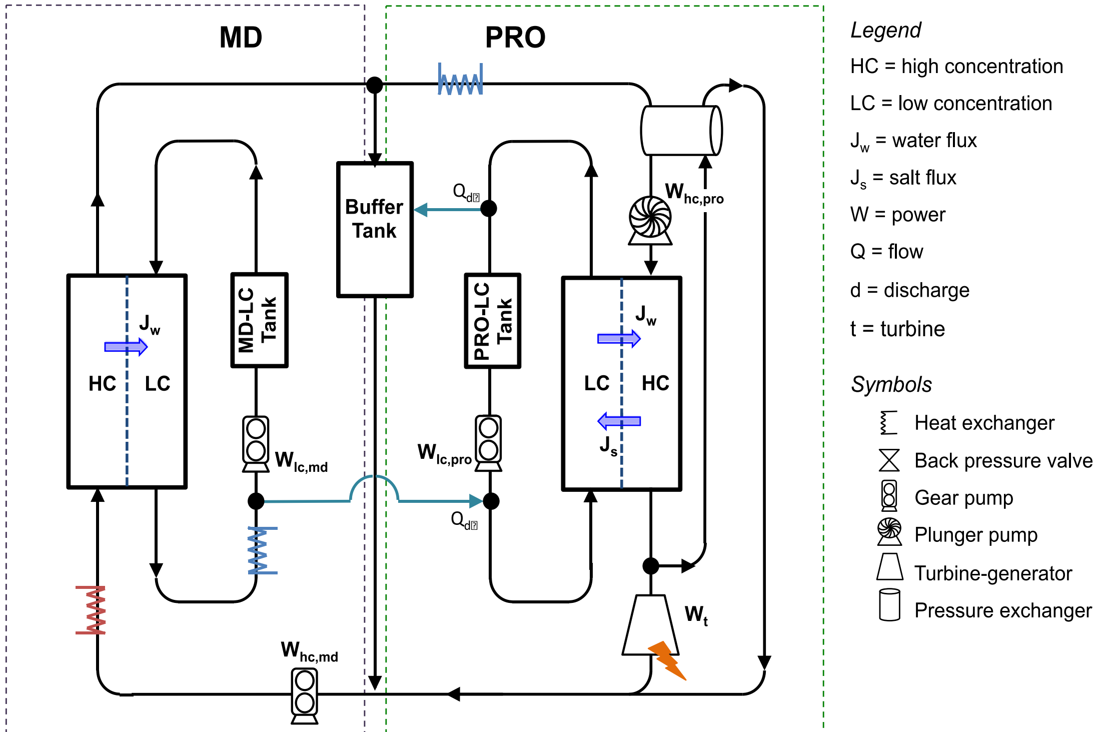

Fig. 1. Simplified schematic of the closed-loop, membrane-based OHE, adopted from Hickenbottom et al. (2017). The OHE couples pressure retarded osmosis (PRO), an osmotically driven membrane process, with membrane distillation (MD), a thermally driven membrane process, to produce electrical energy from otherwise unutilized low-grade heat.

set) is used to convert the hydraulic pressure to useful electric energy. The MD process, a membrane assisted distillation process, utilizes low-grade heat to separate the diluted brine from the PRO processes into a concentrated draw solution and a distilled water stream. The two streams are then resupplied to the PRO process in the OHE. Power density (measured in Watts per m^2), an important performance parameter in PRO and the OHE, can be calculated by multiplying the PRO water flux (membrane permeation rate per unit area of membrane) and the transmembrane hydraulic pressure. Similarly, the MD water flux (measured in liters per m^2 per hr) is a function of the membrane permeability and partial vapor pressure difference, or temperature difference, between the draw solution and distillate stream. Several working fluids have been considered for this process, including organic and inorganic salt solutions (i.e., NaCl, $CaCl_2$, $MgCl_2$, HCOONa, KBr, LiBr, LiCl, $Na(C_2H_5COO)$, and ammonia-carbon dioxide) (Hickenbottom et al., 2016a; McGinnis et al., 2007).

The primary benefits of the OHE over the ORC include lower operating temperatures and less toxic, more environmentally friendly, and safer working fluids. Compared to the ORC, the OHE can operate at temperatures as low as 50 °C, thus reaching broader markets. Additionally, the OHE can utilize non-toxic, non-flammable, chemically stable, non-fossil-fuel based, inorganic (or organic in the future) working fluids, which could make the OHE a more competitive technology over the ORC. A previous study evaluated the technical and economic potential of the OHE over the ORC and found that with future improvements to process performance, the OHE could be a competitive electricity generation process, producing electrical energy at close to $0.10 per kWh (Hickenbottom et al., 2017). However, to fully understand the benefits of the OHE over the ORC, a more holistic approach that evaluates the environmental impacts of the two processes should be taken.

Life-cycle assessment (LCA) is a useful tool that can be employed to quantify environmental impacts associated with all stages of a system's life, or from "cradle-to-grave". LCA is a systematic approach that accounts for resource use and environmental emissions associated with material and energy flows consumed during the construction, operation, and disposal stages of a product or process (Curran, 1996; Stokes and Horvath, 2006). LCAs are commonly used to identify key stages and process components that contribute the largest environmental impacts within a product or process, and to compare environmental impacts of similar products (Raluy et al., 2005a, 2005b, 2006; Stokes and Horvath, 2006; Hancock et al., 2012; Santoyo-Castelazo and Azapagic, 2014). Results from LCAs can be used to make necessary operating, manufacturing, and supply-chain decisions.

Thus, the main objectives of this LCA are to compare the environmental impacts of the OHE and ORC, and evaluate how OHE life-cycle environmental impacts can be reduced. The overall performance of the OHE is highly dependent on MD and PRO process performance (Hickenbottom et al., 2017); therefore, sensitivity analyses were performed on PRO membrane power density and MD operating temperatures. The sensitivity analysis was also extended to include an evaluation of an improved case scenario OHE. The results from the life-cycle impact assessment (LCIA) for the improved case scenario OHE were compared to the ORC (benchmark technology), and CO_2 emissions were compared to a conventional coal power plant (CCPP) and natural gas power plant (NGPP). Ultimately, this information can aid in identifying and recommending potential improvements to the design and operation of the OHE.

2. Methodology

The life-cycle environmental impacts of the OHE and ORC for utilization of LGH for energy production were evaluated. The LCA considers material use for system construction and operation,