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A novel ammonia–carbon dioxide osmotic heat engine for power generation

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Abstract

A novel method of converting thermal energy into mechanical work is presented, using semi-permeable membranes to convert osmotic pressure into electrical power. This method, a closed cycle pressure-retarded osmosis (PRO) process known as an osmotic heat engine (OHE), uses a concentrated ammonia–carbon dioxide draw solution to create high osmotic pressures which generate water flux through a semi-permeable membrane against a hydraulic pressure gradient. The depressurization of the increased draw solution volume in a turbine produces electrical power. The process is maintained in steady state operation through the separation of the diluted draw solution into a re-concentrated draw solution and (nearly) deionized water working fluid, both for reuse in the engine. The use of deionized water working fluid has been shown to allow for high membrane water flux and efficient mass transport, as internal concentration polarization effects are eliminated. Modeling of the engine indicates that membrane power density may exceed 200 W/m^2, given appropriate operating conditions. The thermal efficiency of the engine is predicted to approach a maximum of 16% of Carnot efficiency (maximum theoretical engine efficiency), with practical efficiencies most likely in the range of 5–10% of Carnot efficiency. The temperature of heat used for the engine may be very low (40 °C with a 20 °C ambient temperature), allowing for the production of potentially low cost, carbon neutral power from waste heat, low temperature geothermal reservoirs, or other non-combustion thermal energy sources. This combination of a highly concentrated NH_3/CO_2 draw solution and a deionized working fluid may allow for highly effective power generation from osmotic pressure gradients.

Keywords: Osmosis; Forward osmosis; FO; Ammonia–carbon dioxide; Pressure-retarded osmosis; PRO; Heat engine; Osmotic heat engine; Salinity power

1. Introduction

Increasing rates of energy use are important contributors to human social and economic progress. As per capita energy consumption increases, concomitant increases in standards of living, productivity, and wealth also occur. These trends are linked, and as increasing numbers of the world's population rise out of poverty due to increased economic activity in the developing world, the rate of total global energy use increases apace [1]. This rapidly increasing consumption of energy has correspondingly increased the emission of pollutants and green house gases, along with other deleterious effects. These trends are already observable, and further, potentially dramatic changes are predicted to occur without some significant change of course [2].

In light of this, much research is being conducted on the use of clean renewable energy sources. One emerging source of such energy is the use of differences in salinity between two bodies of water, such as oceans and rivers, to create electrical power. This approach to energy generation is known as "salinity power", or pressure-retarded osmosis (PRO). Early proposals for the development of PRO involved the use of river and seawater streams in an "open" configuration, or alternately, the pairing of one of these with more concentrated streams such as saline waters from the Great Salt Lake and the Dead Sea [3–13].

There are several difficulties, however, posed by the use of open water streams. One of these is the need for pretreatment of feed and draw streams, similar to that required in desalination processes, to prevent fouling of process membranes and components. Another difficulty arises from the low differential osmotic pressures found between many natural feed waters. Seawater, for instance, has an osmotic pressure of approximately 2.53 MPa (25 atm), which does not allow for the high hydraulic pressures

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desirable for efficient power production. In the cases where higher concentration streams are considered, higher hydraulic pressures may be used, but the process efficiency will suffer significantly from internal concentration polarization (ICP) occurring in the support structure of the membrane used for the process [14,15]. This phenomenon is particularly exacerbated by the increased support layer thickness required to resist the increased hydraulic pressures enabled by the more concentrated streams. A final consideration is the need to place power facilities at the interface between natural streams, often areas of considerable environmental importance, such as estuaries, wetlands, and bays.

In order to address these concerns, several investigators have proposed closed cycle PRO systems, intended to use low temperature heat to recycle an osmotic agent. This approach no longer capitalizes on natural salinity gradients, but it does continue to explore the use of osmotic pressure as a medium for the production of work, enabling the conversion of environmentally benign low temperature heat sources to electrical power. In several such proposals, the draw solution was a solution of an ionic salt, such as sodium chloride [3,5,16,17]. Heat applied to the OHE would re-concentrate the draw solution by vaporizing a portion of the water into steam, which would then be condensed to form the deionized working fluid. Other proposals involved the removal of a volatile organic solute, or the chemical precipitation of solutes followed by their re-dissolution [3,17,18]

A primary difficulty faced by the OHEs proposed is poor thermal efficiency, due to high heat input requirements for water and organic solute vaporization. In the case of chemically precipitable solutes, chemical feedstock consumption can pose difficulties to economic operation. An additional challenge to these approaches is the difficulty of obtaining solute separations complete enough to avoid concentration polarization (CP) effects in the feed water. This is not a problem when water is vaporized and re-condensed as distilled working fluid, but could pose a significant problem when using removable draw solutes which are difficult to remove completely. This points to an additional, reoccurring challenge in osmotically driven membrane processes—the difficulty of identifying a solute which may both create high osmotic pressures and be highly removable for reuse. Near complete removability is quite important, as internal concentration polarization effects in the working fluid (feed solution) can drastically reduce membrane water flux [19]. The ideal osmotic heat engine would use a draw solute that is highly soluble, completely removable, has a high diffusivity for effective mass transfer in the membrane system, and requires less heat for solute removal than that required for the vaporization of water or highly soluble organic solutes.

In this paper, we present a novel closed cycle osmotic heat engine. The system uses an ammonia–carbon dioxide draw solution and a deionized water working fluid. The draw solution is highly soluble, osmotically efficient, and contains entirely removable and recyclable solutes. Use of deionized water as a working fluid maximizes membrane mass transfer by eliminating internal concentration polarization effects. The results demonstrate the feasibility of the osmotic heat engine for the practical conversion of low temperature heat sources to power.

2. Closed cycle ammonia–carbon dioxide osmotic heat engine

A draw solution composed of ammonium salts formed by the introduction of ammonia and carbon dioxide into water may be used in an OHE to generate electrical power [20]. A draw solution of this type has several desirable characteristics. The solubility of the ammonium salts is high; the species have relatively low molecular weights and high diffusivities, leading to high osmotic pressures and moderate external concentration polarization effects; the solutes are almost completely removable, in that the ammonium salts, upon heating within a draw solution at an appropriate temperature and pressure (approximately 60 °C at 101.3 kPa (1 atm), for example), will decompose to ammonia and carbon dioxide gases which may be readily removed to levels of <1 ppm; and the thermal energy required for the removal and recycling of these solutes from a quantity of water is significantly less than that required to vaporize the water itself [21].

In the NH_3–CO_2 OHE, the concentrated draw solution is pressurized to a hydraulic pressure lower than its osmotic pressure, a dilute working fluid (in this case water with <1 ppm NH_3 and CO_2) flows through the semi-permeable membrane into the pressurized solution, and this water flux expands the volume of the draw solution, inducing flow through a turbine, producing power. Heat is introduced to the engine to drive a separation of the solutes from the draw solution, resulting in renewed draw and working fluid streams. A pressure exchanger of a type similar to that used in reverse osmosis (RO) desalination is used to maintain the pressure of the draw side of the membrane system in steady state operation [22]. A schematic diagram of the flow and operation principles of a power plant of this type is shown in Fig. 1.

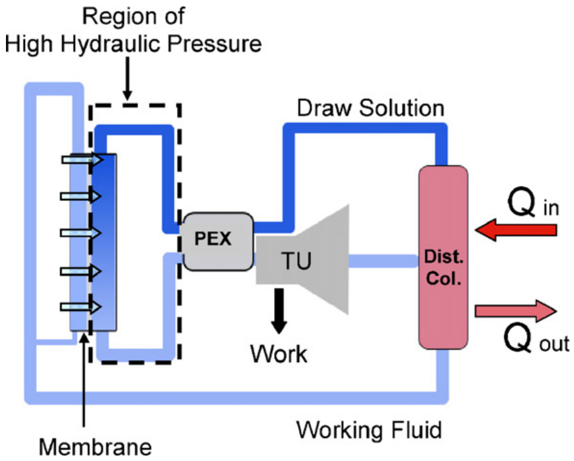

Fig. 1. Schematic of the ammonia–carbon dioxide osmotic heat engine (OHE) for power generation. The working fluid is water containing <1 ppm NH_3 and CO_2, and the draw solution is made up of concentrated ammonium salts. PEX denotes pressure exchanger, TU denotes turbine, and Q_{in} and Q_{out} represent the heat flows into and out of the engine. The dashed line box indicates the region of high hydraulic pressure (on the active layer side of the membrane).

3. Materials and methods

Projections of the performance of the ammonia–carbon dioxide OHE are based on experimental data for water flux, calculations of power conversion efficiency in the turbine and pressure recovery systems, and modeling of the energy requirements for the removal and recycling of the OHE draw solutes.

3.1. Experimental setup

Measurements of water flux through semi-permeable membranes oriented in the PRO configuration (backing layer toward feed, active layer toward draw solution) provide data for estimations of engine performance. Membrane water flux data was obtained using a crossflow membrane cell and associated system components similar to that described in our previous studies on FO desalination [19,23]. The dimensions of the channel are 77 mm long by 26 mm wide by 3 mm deep. Mesh spacers were inserted within both channels to improve support of the membrane as well as to promote turbulence and mass transfer. A variable speed peristaltic pump (Masterflex, Vernon Hills, IL) with a dual pump head was used to pump both the feed and draw solutions in a closed loop. A constant temperature water bath (Neslab, Newington, NH) was used to maintain both the feed and draw solution temperatures. Heat transfer took place within the water bath through inline stainless steel heat exchanger coils which were submerged in the stirred bath. The draw solution rested on a scale (Denver Instruments, Denver, CO) and weight changes were measured over time to determine the permeate water flux. The membrane is placed in the cell such that the draw solution is against the active layer and the feed solution is against the support layer. A complete system diagram is provided in McCutcheon et al. [19].

3.2. Forward osmosis membrane

The membrane used to collect flux data is designed for forward osmosis desalination and was obtained from Hydration Technologies, Inc. (Albany, OR). It is the same type used in previous experiments on forward osmosis desalination [19]. The chemical makeup of the membrane is proprietary, but it is believed to be made of cellulose acetate polymers and will be denoted CA in this investigation. The structure is asymmetric with a separating layer supported by a relatively thin (less than 50 μm) support structure. Further support is provided by a polyester mesh that is embedded within the polymer support layer [23]. However, this membrane is not robust enough to obtain flux data at the high pressures of interest in practical applications of pressure-retarded osmosis.

3.3. NH_3–CO_2 draw solution

Osmotic water flux was determined for a range of draw solution concentrations. The draw solution was made by mixing ammonium bicarbonate salt (NH_4HCO_3) with ammonium hydroxide (NH_4OH), forming a complex solution of ammonium salts, comprised of ammonium bicarbonate, ammonium carbonate, and ammonium carbamate, with the later being the most abundant in concentrated solutions [19]. The amount of NH_4OH added varied depending on the concentration of the draw solution and the temperature at which it was to be used. The amount of NH_4OH was minimized to minimize the concentration of unionized ammonia in the draw solution. Properties of the draw solutions used in modeling of the OHE, including osmotic pressure, density, viscosity, and pH, were obtained with Aspen HYSYS® (Cambridge, MA), in conjunction with an electrolyte property package from OLI Systems Inc. (Morris Plains, NJ).

3.4. Modeling of OHE performance

3.4.1. Modeling OHE water flux

Experimental membrane water flux data (presented later in Section 4.1) are used to calculate fitted (apparent) mass transfer coefficients for predictions of external concentration polarization (ECP) at the interface between the membrane and the concentrated draw solution used to drive engine water flux. ECP effects for a concentrated draw solution in an OHE membrane system are predicted with the fitted mass transfer coefficient and based on film theory [24], with highly concentrated solution ECP effects calculated based on extrapolation from the experimental data. This model fitting and extrapolation is considered necessary in light of the expected significance of ECP effects within the OHE's membrane system, and the inadequacy of traditional film theory to describe mass transfer phenomena in highly concentrated non-ideal solution flows. The predicted membrane fluxes using the fitted coefficient were found to correlate well with observed water flux performance, within the range of experimental data.

Water flux measurements under unpressurized conditions are assumed to predict flux in our pressurized OHE system, following the governing equation for PRO under differing osmotic and hydraulic pressure conditions [25]:

$$J_{\mathrm{w}} = A(\sigma\Delta\pi_{\mathrm{m}} - \Delta P) \qquad (1)$$

Here, A is the water permeability coefficient, σ the reflection coefficient, $\Delta\pi_{\mathrm{m}}$ the difference in osmotic pressures across the membrane between the draw and feed solution at the separating interface (i.e., at the membrane active layer surface), and ΔP is the hydraulic pressure difference between the draw solution side and the working fluid. Note that $\Delta\pi_{\mathrm{m}}$ is calculated from the bulk osmotic pressure of the draw solution after accounting for ECP effects as described above.

We assume $\sigma = 1$ in all calculations because of the relatively high rejection of the FO membrane used in this work, as discussed in our previous publication [19]. Furthermore, the water permeability coefficient, A, is assumed to be independent of the applied hydraulic pressure, implying negligible membrane compaction. The selection of the membrane, operating pressures, and temperature of the system will necessarily influence the accuracy of predictions based on these assumptions.

3.4.2. Modeling of OHE energy production

The power produced by the OHE (W) is a function of the quantity of water moving through its turbine per unit of time

($\dot{V}$), the drop in pressure in that turbine which is equal to the applied hydraulic pressure on the draw solution side (ΔP), and the turbine efficiency (E):

$$W = E\dot{V}\Delta P \tag{2}$$

The turbine efficiency E is typically greater than 90%. The efficiency of the pressure exchanger used to maintain steady state pressurization of the draw solution is typically greater than 95%. The combined efficiency of these two components is approximated, in this modeling effort, to an overall efficiency of 90% for projections of power production, captured in the value of 0.9 for E in Eq. (2). The volume flowing through the turbine per unit time ($\dot{V}$) is equal to the product of the water flux through the membranes of the OHE (J_w) and the total membrane surface area. This flux is a function of both the hydraulic and osmotic pressures of the system, as shown by Eq. (1). Increasing the hydraulic pressure relative to the osmotic pressure increases the power output per unit volume of water through the turbine, but will also reduce the total volume of water by reducing membrane water flux. Reducing hydraulic pressure will have the inverse effect.

3.4.3. *Modeling of OHE energy efficiency*

Thermal efficiency is calculated by measuring the quantity of power produced relative to the quantity of heat used (for the separation and recovery of the draw solution). There are two measures of efficiency which may be considered in evaluating an engine's performance: thermal efficiency and Carnot efficiency. Thermal efficiency is simply the ratio of engine power output over heat input. Carnot efficiency, however, is a measure of the efficiency of an engine relative to that of a Carnot engine, one which produces the maximum theoretical quantity of work from a given heat flow, based on a perfectly reversible process.

The "quantity of heat" component of engine efficiency is calculated based on the heat duty of the distillation column used to separate the ammonia and carbon dioxide from the dilute draw solution, producing a re-concentrated draw solution and deionized working fluid. The column heat duty was modeled with Aspen HYSYS® (Cambridge, MA), in conjunction with an electrolyte property package from OLI Systems Inc. (Morris Plains, NJ), following the procedures used in estimating the energy demands of forward osmosis desalination [21]. Details on the nature of the draw solution, the separation, recovery, and reuse of the draw solutes, and the design characteristics of the distillation column are found in our previous work [21] as well as later in the paper (Section 4.3). The draw solutions used for the OHE modeling had much higher concentrations than those used in our previous desalination studies, but the modeling methods remained identical.

The efficiency of a Carnot engine (η) is given by

$$\eta = 1 - \frac{T_L}{T_H} \tag{3}$$

where T_H is the absolute temperature of heat delivered to the engine (from fuel combustion, for example) and T_L is the absolute temperature at which heat is rejected to the environment. Measuring OHE efficiency against the efficiency of a Carnot engine establishes how effective the OHE is relative to the quality of heat it uses. A geothermal power plant using 200 °C heat, for example, obtaining a thermal efficiency of 20%, would not, by the thermal efficiency measure, seem to be a very efficient plant. The Carnot efficiency of such an engine, however, would be 55%, approximately equal to the Carnot efficiency of a coal fired power plant operating at 537 °C [26]. This is a particularly useful method of comparison between heat engine technologies when considering heat sources as low as 20 °C above ambient temperatures, where maximum theoretical thermal efficiencies are quite low.

4. Results and discussion

4.1. *Influence of temperature and draw solution concentration on membrane water flux*

As the difference in osmotic pressure between two solutions increases, the flux through a semi-permeable membrane separating the two will increase as well. This relationship is not linear, due to concentration polarization effects at the surface of the membrane [25]. In PRO mode (draw solution on active layer side of membrane) with deionized water as the feed, only external concentration polarization is expected to occur, assuming very high rejection of salts by the membrane [19]. Fig. 2 illustrates the relationship between water flux and draw solution concentration for the CA membrane.

Data is shown for 20 and 40 °C, with the feed and draw solutions in each case isothermal. Flux is shown relative to the osmotic pressures of the draw solutions. Higher temperatures lead to higher water fluxes due to the effects of temperature on the membrane water permeability and the diffusivity of the draw solutes. With the FO membrane operated in the PRO mode with a deionized water feed, water flux exceeds

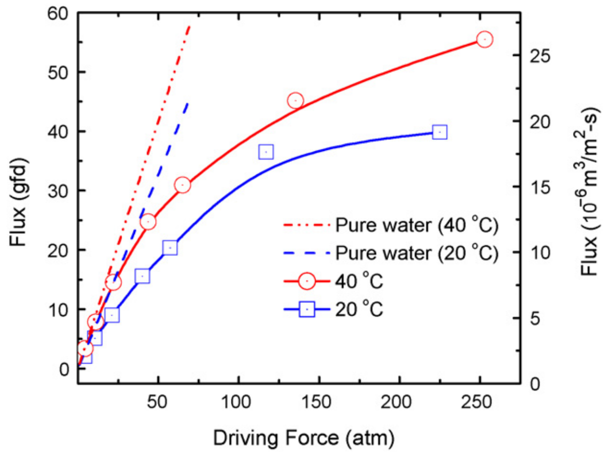

Fig. 2. Osmotic water flux performance of the CA membrane using an unpressurized NH_3/CO_2 draw solution with deionized water as the feed stream, with feed and draw solutions isothermal. The driving force is calculated based on the bulk osmotic pressure of the draw solution. Data are shown for 20 and 40 °C conditions. Dashed lines indicate pure water hydraulic permeability determined from reverse osmosis tests with the same membrane. Differences between these lines and experimental data are due to external concentration polarization.

25 m^3/m^2-s (or 50 gallons per square foot of membrane per day, GFD). As discussed earlier, the nonlinear relationship shown is due to ECP, caused by dilution of the draw solution at the membrane surface on the permeate side of the membrane. These experimental flux data are used to calculate the power output of the OHE as described below.

4.2. OHE power output

One criterion for optimizing the OHE is to select hydraulic and osmotic pressures which produce the highest power output per membrane area, or highest membrane "power density". The power density was calculated based on membrane water flux, draw solution hydraulic pressure, and anticipated ECP effects in the OHE membrane system. The ECP effects were calculated using a fitted mass transfer coefficient of 1.78×10^{-5} m/s, determined through experimental flux measurements in the PRO mode. The combined efficiency of the hydroturbine and pressure recovery device (Fig. 1) was assumed to be 90%. The relationship between the osmotic and hydraulic pressures in the OHE, relative to the membrane power density, is shown in Fig. 3.

The modeling indicates that the maximum membrane power density is achieved when the hydraulic pressure is approximately 50% of the osmotic pressure. For an OHE with a hydraulic pressure of 10.13 MPa (100 atm), the power density provided by use of a 4.6 M draw solution producing 19.16 MPa (197 atm) of osmotic pressure is approximately 170 W/m^2. This is quite high compared to the power densities expected of river/seawater salinity PRO power plants, under 4 W/m^2 [12].

The power density may be further increased, however, by increasing the crossflow velocity of the draw solution stream (to reduce ECP effects) or the hydraulic pressure of the OHE membrane system. Modeling of an OHE with significantly increased crossflow velocities (5 m/s in a 0.05 cm high flow channel), indicates that OHE power densities would be increased by approximately 61% over those of a membrane system with the fluid dynamics of the test cell used in this study (0.46 m/s in a 0.3 cm high channel). For an OHE operating at 10.13 MPa (100 atm) hydraulic pressure, the maximum power density would be 274 W/m^2 in this case.

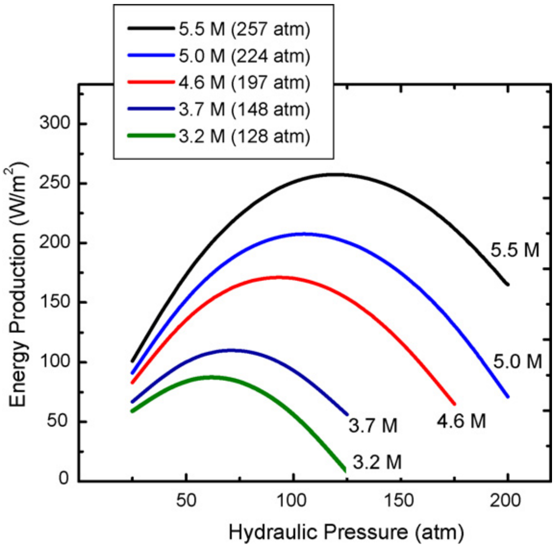

Fig. 3. Membrane power density (W/m^2), relative to hydraulic and osmotic pressures in the OHE. Each curve corresponds to a fixed ammonia–carbon dioxide draw solution concentration. Maximum power density is achieved with a hydraulic pressure which is approximately 50% of the draw solution osmotic pressure.

Modeling of an OHE with a 20.26 MPa (200 atm) hydraulic operating pressure indicates that power densities would be increased by an additional 47% over those of a 10.13 MPa (100 atm) system. Increased crossflow velocity, however, will result in additional power consumption, and increased hydraulic pressure will require more expensive process components. These operating conditions will necessarily be factors in process optimization, balanced against correlating factors of process fluid pump power consumption and equipment capital and replacement costs.

4.3. OHE efficiency

The Carnot efficiency of the OHE was modeled over a range of osmotic and hydraulic pressures. In the calculation of engine thermal efficiency, the heat and electrical duties of the draw solute separation and recycling process are compared to the electrical production of the OHE power generating turbine for the combination of osmotic and hydraulic pressures examined. Because the electrical energy needed for the draw solute separation and recycling is negligible, the thermal efficiency is practically the ratio between the electrical energy produced by the OHE and the thermal energy required for the draw solute separation. This efficiency is compared to the theoretical efficiency of a Carnot engine operating with the same high and low temperature heat streams, giving a "percentage of Carnot efficiency" measure of OHE performance.

To determine the heat and electrical duty of the draw solute removal and recycling process, a draw solution of sufficient concentration to produce the osmotic pressure desired is specified in a Hysys® chemical simulation model. This solution stream is directed to a distillation column with characteristics appropriate for the removal. One example of such a model specifies a single distillation column, effecting the separation of draw solutes from a 6 M (CO_2 basis) draw solution stream (which generates 31.94 MPa (315.26 atm) osmotic pressure in the OHE membrane system), containing structured packing 2.35 m (7.7 ft) in height (30 theoretical stages), supplied with heat at 50 °C. A column of this type operates at a bottom pressure and temperature of 10.62 kPa (0.1048 atm) and 46.96 °C (given a 3 °C ΔT in the reboiler heat exchanger), and a tops pressure and temperature of 10.54 kPa (0.1040 atm) and 35.55 °C. The stream fed to the top of the column is preheated to 32 °C with an energy requirement of 3196.8 MJ/m^3 (per m^3 working fluid produced). The column heat duty is 3454.6 MJ/m^3, supplied to the reboiler. Supplementary heating required to maintain all streams at specified temperatures is 385.7 MJ/m^3, for a total heat duty of 7037.1 MJ/m^3. The electrical duty for fluid pumping in the separation process is relatively negligible (0.48 MJ/m^3). A summary of the heat and electrical duties required for the separation of the

Table 1
Several characteristics of draw solutions used in the modeling of OHE efficiency and relevant heat and electrical duties for the draw solute separation and recycling

Draw solute concentration (M)	Osmotic pressure (atm)	NH_3/CO_2 ratio	Heat duty (MJ/m^3)	Electrical duty (MJ/m^3)
1	43.7	1.1	358.0	0.12
2	84.4	1.2	593.4	0.13
3	120.1	1.2	865.7	0.16
4	157.8	1.3	1319.0	0.19
5	229.6	1.6	2847.7	0.26
6	319.7	1.8	7037.1	0.48

The molar concentration of the draw solution is given on a CO_2 basis. Also presented are the N/C (or NH_3 to CO_2) ratios of the draw solutions and the corresponding osmotic pressures at 40 °C. Heat and electrical duties are those calculated by Hysys® as necessary for separation of the draw solution into a concentrated stream and working fluid stream containing <1 ppm NH_3. All data shown here is for the case of heat supplied at 50 °C.

draw solute at typical concentrations used in our simulations is given in Table 1. This table also presents some of the properties of the draw solution that are relevant to the modeling of the OHE performance.

The overall Carnot efficiency of the OHE was calculated based on modeling of the type described above, over a range of supplied heat temperatures. Over a variety of temperatures, the efficiencies were remarkably consistent. In Fig. 4, the Carnot efficiencies for OHEs operating with 50 °C heat are shown, over a range of osmotic and hydraulic pressures in the OHE membrane system. For each combination of pressures, the temperatures were held constant, with a high temperature, or temperature of energy supplied, of 50 °C, and a low temperature, or temperature of the ambient environment, of 25 °C.

The results indicate that the highest engine efficiency is obtained when the difference between osmotic and hydraulic pressures approaches zero. Given equal osmotic and hydraulic pressures at equilibrium in a zero-flux condition, increases in osmotic pressure will increase membrane water flux, thereby increasing the amount of power produced by the OHE turbine. Increases in osmotic pressure, however, are achieved by increasing the draw solution concentration. Higher concentration draw solutions require more energy for solute removal and recycling in the form of supplied heat. Therefore, as osmotic pressure is increased, power production, membrane water flux, and heat duty required by the solute recycling system all increase concurrently.

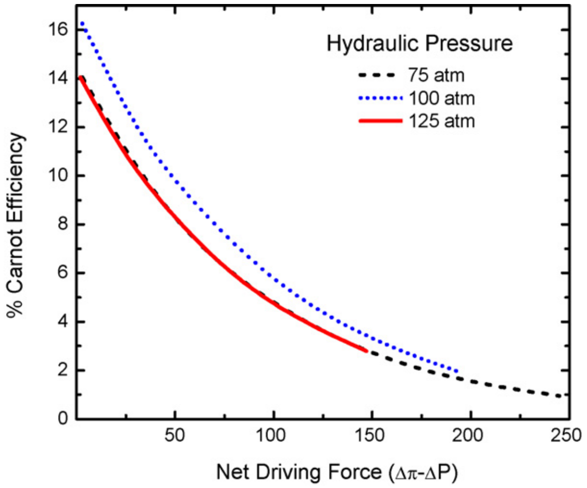

Fig. 4. OHE engine efficiency as a percentage of Carnot engine efficiency, relative to the difference between the hydraulic and osmotic pressures of the draw solution. For a high temperature of 50 °C and a low temperature of 25 °C, the percentage of maximum theoretical engine efficiency (Carnot) reaches a maximum of approximately 16% as the net driving force ($\Delta\pi - \Delta P$) approaches zero. The osmotic pressure $\Delta\pi$ is based on the bulk osmotic pressure of the draw solution.

The distillation column used for the solute recycling system is, however, inefficient in its removal of NH_3 and CO_2 from the dilute draw solution. Some water vapor is also removed, requiring heat which may not be converted to power production. As the concentration of the draw solution is increased, the amount of water vapor created in the distillation column increases as well, and this inherent inefficiency of separation results in decreasing OHE efficiency overall. The increase in osmotic pressure does, however, result in increased water flux, which benefits OHE operation through increased membrane power density. Higher membrane power densities require less membrane area for a given engine capacity, and therefore less membrane cost. This represents a tradeoff between membrane capital cost and engine efficiency, a balance which must be optimized in the design of an OHE system.

5. Concluding remarks

As our results indicate, although overall engine efficiency is fairly low, approaching a maximum of 16% of Carnot efficiency, and a probable operating efficiency of 5–10%, the power output per membrane area can be quite high, in excess of 250 W/m^2 of membrane area. Should the OHE use thermal energy sources in the range of 40–100 °C, the cost of the energy input to the engine may approach negligibility. The most important consideration in such a case would then be the capital and labor costs of the process and their impacts on the cost of electricity produced.

Factors which will impact the total cost include, in addition to the capital cost of the membrane system, the capital cost of heat exchange equipment for heat supply to the solute recycling system and heat rejection to the ambient environment. The lower the difference in temperatures between the supply and reject temperature reservoirs (low temperature geothermal heat supply and air cooling, for example), the lower the thermal efficiency of a heat engine will be, with resultant increased heat exchange area and cost. The feasibility of the use of an OHE will depend on detailed analyses and optimization of the relationship between membrane power density, heat exchange surface area, the quantity and quality of the thermal energy source, and the power output requirements of the end users of the OHE process.

The use of an ammonia–carbon dioxide osmotic heat engine may, given these considerations, allow for economically competitive power production from diverse energy sources, including for example, heat from the reject streams of existing power plants, otherwise unproductive low temperature geothermal heat sources, low-concentration solar thermal energy, biomass heat (non-combustion), or ocean thermal energy conversion. In all these cases, the process would produce power which is renewable and carbon-free.

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