Low-Grade Waste Heat Recovery via an Osmotic Heat Engine by Using a Freestanding Graphene Oxide Membrane

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ABSTRACT: The osmotic heat engine represents a new and promising technology for the harvesting of low-grade waste heat from various sources. However, the lack of an adequate semipermeable membrane hinders the technology’s advancement. In this study, we investigated the application of a freestanding graphene oxide membrane (GOM) for energy generation in an osmotic heat engine. The synthesized GOM has a water permeability coefficient of 4.4 L m⁻² h⁻¹ bar⁻¹ (LMH-bar). The internal concentration polarization in the osmosis filtration system can be minimized because no membrane support layer is needed for the freestanding GOM. As a result, high water flux and high power density are obtained. For example, under an applied hydraulic pressure of 6.90 bar, with a 2 M draw solution of ammonium bicarbonate solution, a power density of 20.0 W/m² is achieved. This study shows that the freestanding GOM is promising for application in the osmotic heat engine. Future research regarding improving the mechanical properties and water stability of the GOM is beneficial for further advancing the technology.

INTRODUCTION

Current excessive reliance on nonrenewable, carbon-emitting fossil fuels to generate energy creates severe problems such as climate change and environmental pollution.¹,² Developing sustainable energy technologies and enhancing the energy utilization efficiency of existing industrial processes are two effective methods to reduce the negative impact of fossil fuels.³−⁵ More than 30% of the U.S. energy supply is consumed by industrial processes and 20−50% of that energy is lost in the form of waste heat.⁶,⁷ Utilizing this waste heat can increase the energy efficiency of those industrial processes and also prevent thermal pollution,⁷ thereby transforming an environmentally harmful process to an environmentally benign one. In addition, a significant amount of untapped heat energy is also available from geothermal and solar-based processes.⁸

The most efficient way of using untapped waste heat is directly utilizing it for heat pumps and space heating. However, direct onsite usage is largely confined to the locality of the waste heat sources.⁹ Hence, when matching needs for direct utilization are absent near the heat sources, converting the waste heat into electricity becomes the only option available. Unfortunately, less than 10% of the waste heat from industrial processes has the high quality needed for electricity generation via existing technologies.¹⁰ Current commercial technologies such as the organic Rankine cycle can operate with a relatively high-grade waste heat source (temperature of 90−300 °C).⁵ However, a large amount of waste heat with a temperature of 45−60 °C is produced during industrial processes and is unrecoverable via existing technologies.¹¹,¹² Besides, a large amount of thermal energy exists in the Earth’s crust. To convert geothermal energy into electricity, access to a high-temperature heat source by drilling is necessary because the more easily accessible low-grade heat cannot be utilized to generate electricity with existing methods.⁹,¹³ The development of new technologies that can efficiently convert low-grade heat into electricity is, thus, beneficial toward utilizing waste heat as a sustainable energy source.

The membrane-based heat engine is a promising technology that can convert low-grade heat into electricity.¹⁴,¹⁵ This technology consists of a closed-loop power system made up of two components: electricity generation and thermal separation (Figure 1). The electricity generation component converts the energy released from the controlled mixing of two solutions with different salinity gradients (salt concentrations) into electricity.¹⁴ The principle of pressure-retarded osmosis (PRO) is utilized in the heat engine to produce pressurized water flow. With the help of a semipermeable membrane, water molecules can transport from the low salt concentrated solution (feed solution) to the high salt concentrated solution (draw solution). The kinetic energy from the pressurized draw
solution is then converted to electricity by using a mechanical turbine. Because osmotic pressure acts as the driving force in the electricity generation component, the technology is best represented by the osmotic heat engine. The osmotic heat engine is the most widely studied membrane-based technology for low-grade heat harvesting; however, other membrane-based systems have also been proposed and evaluated. Alternatively, by regulating the ion transport of different charges, an osmotic ion flux can be generated inside the system. The ion flux can then be converted to an electron flow by using electrodes, whereby electricity can be generated. Unlike the osmotic heat engine, the ion flux generating technology uses permselective ion-exchange membranes to produce an osmotic ionic current known as reverse electrodialysis to power the heat engine.

The thermal separation component of the osmotic heat engine regenerates the draw solution and feed solution by using waste heat as an energy source. Different working electrolyte solutions have been evaluated to maximize energy production. Generally, the salts that form the electrolyte solutions should pose high solubility in water (or other solvents), which provides a large driving force, and should be easy to regenerate. Inorganic ionic salts, such as sodium chloride, were investigated in previous studies. In those cases, the waste heat was used to reconcentrate the draw solutions by vaporizing part of the water. However, the energy-intensive vaporization process leads to a low thermal efficiency. Alternatively, solute extraction was applied to regenerate the draw and feed solutions. The salt ions transferred from the draw solution into the feed solution can be extracted during the thermal separation step. Comparing to conventional ionic salts, the thermolytic salts (ammonium bicarbonate) were found to have a higher conversion efficiency when utilizing the low-temperature heat sources. The thermolytic salts in the aqueous phase can be converted to gaseous species (ammonia and carbon dioxide) upon heating; then, the releasing and resolubilization of the gas molecules will lead to the regeneration of the feed and draw solutions, respectively.

Despite the great progress that has been made in thermodynamic analysis, techno-economic assessment, and alternative solute and solvent investigation, research on the development of membranes for the osmotic heat engine is scarce. The semipermeable membrane plays an important role in the osmotic heat engine; the major obstacle to improving the technology is the lack of an adequate membrane. The transport properties of the membrane determine water flux and, thus, the power generation of the entire system. Conventionally, a thin-film composite (TFC) membrane is applied in the system to generate permeate water flux. However, the existence of the membrane porous support layer results in an internal concentration polarization (ICP), which decreases the effective driving force across the membrane and adversely affects the performance of the system.

In this study, we investigated the application of a freestanding graphene oxide membrane (GOM) in the osmotic heat engine. GOM has been applied in many separation practices because of its excellent transport properties and sharp molecular cutoff. By using a freestanding GOM, we were able to minimize the effect of ICP, increase water flux, and...
eventually enhance the energy generation of the osmotic heat engine system. Although the freestanding GOM has an even higher reverse salt flux during the osmosis process, because of the elimination of the membrane porous support layer, salt ions have nowhere to accumulate. Thus, a large driving force across the GOM can be maintained during the process (Figure S1b). As a result, high water flux can be obtained, which is beneficial for power generation in the osmotic heat engine. The water and ion transport properties of the GOM have been extensively studied. By combining experimental work and theoretical modeling, the feasibility of the freestanding GOM for application in the osmotic heat engine was explored and the results are discussed herein.

RESULTS AND DISCUSSION

Material Characterization. According to the C 1s XPS spectra (Figure 2a), both nonoxygenated carbon (C–C, 285.60 eV) and oxygenated carbon (C–O, 287.72 eV, and C=O, 288.50 eV) can be identified from the synthesized graphene oxide (GO). The GO sheets were dispersed on a silicon wafer and then characterized by scanning electron microscopy (SEM). The SEM image (Figure 2b) indicates that the GO sheet has an average dimension of around 2 μm. The photograph (Figure S2) of the synthesized freestanding GOM indicates that it is circular with a uniform thickness. The surface morphology of the freestanding GOM was characterized by using SEM, and a smooth surface was observed (Figure 2c), which is similar to previous studies.35,36 The thickness of the freestanding GOM was determined from membrane cross-sectional SEM images and verified by using a micrometer. At least three samples were measured via SEM, and the average value was reported to represent the membrane thickness. To ensure that the synthesized GOM has an adequate water permeability coefficient, we have made the GOM as thin as possible. The thinnest GOM we were able to synthesize has a thickness of 1.93 ± 0.07 μm. A GOM with a smaller thickness does not have enough mechanical stability and tends to break easily. The GOM cross-sectional SEM image (Figure 2d) reveals a well-packed layered structure throughout the GOM sample. The layered structure of the GOM was evidenced via its X-ray diffraction (XRD) pattern (Figure S4). The dry and wet GOMs have an interlayer spacing of 0.83 and 1.54 nm, respectively. The GOM was extensively characterized in terms of transport properties and power generation performance in the osmotic heat engine.

GO Membrane Water and Ion Transport Properties. Water permeability coefficient (A) of the freestanding GOM was determined by using a modified reverse osmosis (RO) testing cell. Figure 3a lists the water permeability coefficient of the GOM under the different hydraulic pressures. The water permeability coefficient is consistent across all of the measured hydraulic pressure ranges (from 2.07 to 6.90 bar), indicating negligible membrane compaction. A water permeability coefficient of 4.4 L m⁻² h⁻¹ bar⁻¹ (LMH-bar) was determined for the GOM by averaging values obtained from different hydraulic pressures. The burst pressure of the GOM was determined to be between 6.90 and 8.97 bar. During the experiment, when the hydraulic pressure increased from 6.90 to 8.97 bar, a sharp increase in water flowrate occurred across the membrane, indicating that under the hydraulic pressure of 8.97 bar, the membrane could not maintain structural integrity. The membrane salt permeability coefficient (B) was calculated based on the results from the modified RO tests. With a transmembrane hydraulic pressure of 3.45 bar, 50 mM NaCl and NH₄HCO₃ solutions were used as the feed solutions. For the NaCl solution, a rejection of 32.64% yields a salt permeability coefficient (B) of 11.13 LMH. For the NH₄HCO₃ solution, a slightly higher rejection of 34.58% results in a salt permeability coefficient of 10.20 LMH. The relatively high salt permeability coefficient of the GOM might be due to the large interlayer spacing upon hydration (1.54 nm). The spacing among the GO layers is larger than the hydrated diameters of the ions so that the ions can pass through the GOM especially when there is an applied hydraulic pressure.

The GOM was also tested under a lab-scale forward osmosis (FO) system to further characterize the transport properties as...
well as estimate the PRO power generation preformation. First, 1 M NaCl solution and deionized (DI) water were chosen as draw and feed solutions, respectively. To investigate the influence of solution pH on the transport of the GOM, draw and feed solutions with different pH values were used. Figure 3b shows the water flux and (reverse) salt flux under various pH values. The water flux and salt flux remained almost unchanged across the entire investigated pH range, suggesting that solution pH has negligible influence on the GOM water and salt transport in the osmosis process. The carboxyl group, existing at the edge of the GO sheets, has been reported to play an important role in ion exchange and adsorption. As a weak acid, carboxyl has a $pK_a$ value of about 4.8. When the solution pH increases, carboxyl groups become deprotonated, which can increase the charge density of the GOM. As a result, the transport of the charged species, such as ions, can be potentially influenced. However, the ion transport of GOM during osmosis was unaffected. A possible explanation is that the density of the carboxyl group is not high enough, so the influence of the carboxyl on the ion transport during osmosis is not apparent.

Then, the membrane water flux was measured by varying the concentration of the draw solution. Figure 3c shows the water flux changing with the increase of the NaCl draw solution concentration. When DI water acts as the feed solution, the water flux increases almost linearly with the increase of the draw solution concentration. The change of water flux shares the same trend with 0.1 M NaCl solution acting as the feed solution. However, because of the slightly decreased concentration gradient, the effective driving force and the water flux across the GOM are also reduced. The linear increase of water flux with the increase of the draw solution concentration indicates the minimization of the ICP. ICP is a major limiting factor hindering the performance of the FO and PRO membranes. For a conventional TFC membrane, when salt ions get trapped inside the membrane support layer, the effective driving force across the membrane can decrease significantly, leading to a much lower water flux than expected. However, by using the freestanding GOM, the ICP can be reduced because of the elimination of the membrane support layer. As a result, a larger driving force can be maintained and a higher water flux can be achieved. Similar water flux values were obtained when replacing the NaCl solution with an NH$_4$HCO$_3$ solution, as shown in Figure 3d. The application of the freestanding GOM results in a significant reduction of the membrane ICP, which is beneficial for power generation in the PRO and osmotic heat engine systems.

**Projected Power Density and Energy Efficiency in the Osmotic Heat Engine.** The electricity generation component of the osmotic heat engine determines how much electricity can be generated from the system. Power density in terms of unit membrane area is calculated based on the membrane water flux and the draw solution hydraulic pressure. Because the freestanding GOM does not have a support layer and the water flux is almost proportional with the draw solution concentration (Figure 3c,d), the membrane ICP is neglected during the power density estimation. The membrane structural parameter ($S$) is used to quantify the influence of ICP on water flux and power density; thus, the structural parameter is assumed to be zero in this study.

According to our calculation (using eqs 2 and 3) as well as previous studies, the power density ($W$) increases with the increase of the applied hydraulic pressure on the draw solution side. When the hydraulic pressure is approximately half of the osmotic pressure difference between feed and draw solutions, peak power density is achieved (Figure S5a). Figure 4a lists the calculated peak power density values from the different NH$_4$HCO$_3$ draw solutions (DI water as the feed solution). As draw solution concentration increases from 0.5 to 2 M, the peak power density increases from 7.3 to 56.3 W/m$^2$. Because the determined burst pressure is between 6.90 and 8.97 bar, the GOM in its current state cannot withstand half the osmotic pressure differences. The corresponding power density values were calculated for each hydraulic pressure below the burst pressure. As shown in Figure 4b, the power density increases with the increase of the hydraulic pressure on the draw solution side. Under a hydraulic pressure of 6.90 bar,
the membrane power density reaches 6.7, 12.8, 16.9, and 20.0 W/m² when the NH₄HCO₃ draw solution concentrations are 0.5, 1, 1.5, and 2 M, respectively. The power density values, when considering the burst pressure, are lower than the peak values; however, they are higher than the power density values from previous studies under similar conditions (Table S1).¹⁵,²³,²⁴,⁴⁴

Energy efficiency of the osmotic heat engine measures the ratio of the thermal energy that can be converted into electricity. By assuming that the temperature of the heat source is as low as 50 °C, an energy efficiency analysis on the osmotic heat engine that incorporates the GOM was conducted. It should be noted that according to our developed model (SI1), the energy efficiency is not influenced by the scale of the system. Instead, the system energy efficiency was found to increase with the increase of applied hydraulic pressure on the draw solution side (Figure S5b). When the applied hydraulic pressure equals the osmotic pressure difference between the feed and draw solutions, the system energy efficiency reaches its highest value (around 5%), though the power density is almost zero under such hydraulic pressure. When the peak power density is reached, the osmotic heat engine achieves an energy efficiency of 2.48% (Figure 4c). The estimated optimal energy efficiency does not change with the draw solution concentration. When a draw solution with higher salt concentration is used, a higher peak power density can be achieved, which is beneficial to energy generation. However, more thermal energy is needed to regenerate the feed and draw solutions, making the overall energy efficiency unchanged. The applied hydraulic pressure was found to have a significant influence on energy efficiency: when the hydraulic pressure increases, the energy efficiency also increases (Figure 4d). For example, when the hydraulic pressure increases from 2.07 to 6.90 bar, the energy efficiency increases from 0.41, 0.21, 0.14, and 0.10 to 1.38, 0.69, 0.46, and 0.35% with the draw solution concentrations of 0.5, 1, 1.5 and 2 M, respectively. Although the system energy efficiency keeps increasing with the increase of the applied hydraulic pressure, the power density decreases when the applied hydraulic pressure is larger than half the osmotic pressure difference. At the same hydraulic pressure, a lower draw solution concentration leads to higher energy efficiency; this is because when the draw solution concentration is lower, less energy is needed to regenerate the feed and draw solutions.

The osmotic heat engine outperforms existing technologies in terms of the feasible working temperature. The system can generate electricity from heat sources of very low temperature as long as the solutes can be dissociated at such temperature. According to previous studies, the NH₄HCO₃ solution can be ideally regenerated at a temperature of about 50 °C.²³ In this study, the membrane ICP is largely reduced by using the freestanding GOM. The reduction of membrane ICP can significantly increase the effective driving force across the membrane. For the TFC membrane, high water flux and high power density can be achieved when DI water is used as the feed solution in the PRO system.¹⁴ However, the current commercially available TFC membranes are not powerful enough to completely prevent the reverse salt permeation. When the salt ions transport across the membrane active layer and accumulate inside the support layer, ICP occurs.¹⁵,⁴⁵ Besides, it is a daunting task to eliminate all of the solutes from the feed solution during the thermal separation process. Severe ICP can significantly reduce the water flux and power density of the osmotic heat engine. However, by using the freestanding GOM, a high water flux can still be achieved even when the feed solution contains a high concentration of salt ions (Figure 3c,d); thus, a high power density is guaranteed. Because high power density in the osmotic heat engine is essential to minimize facility cost and parasitic pumping losses, the enhanced power density in this study represents a step forward toward the large-scale application of the technology.

The results from this study show that when the applied hydraulic pressure is lower than half of the osmotic pressure difference, both the power density and energy efficiency increase with the increase of the applied hydraulic pressure. The burst pressure of the GOM became the limiting factor for energy generation. The freestanding GOM in its current state can only resist about 6.90 bar of hydraulic pressure in the PRO system. The mechanical strength and thus the burst pressure might be increased by increasing the GOM thickness. However, when the GOM thickness increases, the water permeability coefficient decreases, which would hinder the performance of the osmotic heat engine. In addition, the low stability of the GOM in water has been singled out as a key factor preventing the GOM from being applied on a large scale. It is quite possible that the low stability of GOM in water and the low burst pressure in the PRO system are related. Although GOM was reported to have good mechanical properties in its dry state, the swelling of GOM upon hydration (indicated by the XRD result in this study) can decrease its stability as well as mechanical strength. Fortunately, many recent studies have focused on increasing the stability and mechanical properties of the GO-related membranes.⁴⁷−⁴⁹ The positive results from those studies can be readily applied to design GOM with better performance. The high salt permeability coefficient values of the GOM can hinder the system energy generation performance. To minimize the reverse salt flux, a thermolytic salt solution with reduced salt permeability coefficient, such as 1-cyclohexylpiperidine−H₂CO₃ solution, can be applied.⁵⁰ By coupling the freestanding GOM with this draw solution, the power output of the osmotic heat engine can be further enhanced. Besides, the power generation results from this study are based on coupon-scale measurements. It is recognized that the trade-off between power density and energy efficiency is an intrinsic challenge to the full-scale system and the average power output might be much lower in full-scale operation.⁵¹,⁵² An evaluation of the GOM impact in a larger scale system is necessary, and a better design of the power generation system could enhance power generation under field conditions.

To summarize, the current study explores the suitability of a freestanding GOM in the osmotic heat engine for low-grade waste heat harvesting. Our efforts to develop GOM with good transport properties and high power density are essential to the success and further enhancement of system performance.

**CONCLUSIONS**

In summary, we have synthesized and investigated the performance of a freestanding GOM in the membrane-based osmotic heat engine. The water and ion transport properties of the freestanding GOM have been investigated. The GOM has an average water permeability coefficient of 4.4 LMH-bar. Because of the elimination of the membrane support layer, the ICP is largely minimized in the osmosis system. The GOM can achieve high power density in the osmotic heat engine using ammonium bicarbonate solution as the working fluid. Under
an applied hydraulic pressure of 6.90 bar, the membrane power density reaches 6.7, 12.8, 16.9, and 20.0 W/m² when the draw solution concentrations are 0.5, 1, 1.5, and 2 M, respectively. The system energy efficiency was found to increase with the increase of the applied hydraulic pressure. The current study concludes that the freestanding GOM is suitable for application in the osmotic heat engine. However, future research on the development of GO-based membranes with higher burst pressure and better stability in water is needed to further advance this carbon-neutral and transformative technology.

## EXPERIMENTAL SECTION

**Synthesis of GO Membranes.** GO dispersions were synthesized via a modified Hummer’s method for which graphite was oxidized using a combination of sodium nitrate, concentrated sulfuric acid, and potassium permanganate under a controlled reaction temperature. Then, hydrogen peroxide was added to terminate the oxidation reaction. The mixture was then washed several times with DI water. Finally, the precipitate was redispersed in DI water to form GO dispersion with a concentration of 1 g/L.

The freestanding GOM was synthesized by using a vacuum filtration method. The as-prepared GO dispersion was first diluted with DI water and then filtered through an inorganic Whatman anodisc AAO 47-mm diameter filter with a 0.2 μm pore size (Whatman Inc., Clifton, NJ, USA). The AAO filter was proven successful when used to synthesize freestanding GOM with good stability. The GOM can be easily peeled off the AAO filter, forming a freestanding membrane after the filtration process is complete. According to previous studies, the water permeability coefficient of the GOM decreases with the increase of membrane thickness; therefore, in this study, we tried to synthesize freestanding GOM, making it as thin as possible to ensure a high water permeability coefficient but, at the same time, we kept enough thickness to ensure reasonable mechanical strength.

**Characterization of GOM.** GO chemistry was analyzed by a K-Alpha X-ray photoelectron spectrometer system (K Alpha, Schaumburg, IL, USA). SEM images were obtained on a Hitachi SU8010 field emission SEM system (Hitachi High Technologies America, Inc., Schaumburg, IL). The thickness of the GOM was determined via cross-sectional SEM images and verified by using a micrometer. X-ray diffractometry was carried out on a PANalytical X’Pert PRO Alpha-1 diffractometer (40 kV, 40 mA) (Malvern Panalytical B.V., Almelo, Netherlands) for both dry and wet GOM samples. The wet sample was prepared by soaking the GOM in DI water for 24 h before characterization.

**Measurements of GO Membrane Transport Properties.** The membrane water permeability coefficient ($A$) and salt permeability coefficient ($B$) were measured via a modified RO test cell by using DI water and salt solutions, respectively. A previous study pointed out that in a conventional RO experiment, the membrane does not deform because the permeate channel is supported by a porous frit. Hence, the measured membrane $A$ and $B$ values in the RO testing cell would be different from that of a deformed membrane in a PRO testing cell. In this study, the porous frit in the RO testing cell was replaced by a porous mesh-type SEPA CF medium foulant spacer (Sterlitech Corp., Kent, WA, USA) (Figure S2) to determine the $A$ and $B$ values suitable for PRO. The modified RO testing cell has an effective area of 4.1 cm².

During the experiment, the feed and permeate channels of the modified RO testing cell acted as draw and feed solution channels of the PRO cell, respectively (Figure S2). The influent feed solution was pressurized and circulated in the feed channel with a flow rate of 400 mL/min, and the permeate was weighted on a minute basis using a digital balance. DI water was used as the permeate for the determination of the water permeability coefficient ($A$). The weight change of the permeate was used to calculate the water flux and water permeability coefficient. The membrane was tested for 1 h under each applied hydraulic pressure (from 2.07 to 8.97 bar), and the water permeability coefficient ($A$) was determined by dividing the water flux by the hydraulic pressure ($A = J_w / \Delta P$).

The membrane was tested under a hydraulic pressure of 3.45 bar (50 psi) for 1 h to determine the salt permeability coefficient ($B$). The membrane salt rejection ($R$) was tested in the modified RO cell by using both sodium chloride solution (NaCl, 50 mM) and ammonium bicarbonate solution (NH₄HCO₃, 50 mM). A conductivity meter was used to measure the conductivity of the feed and permeate solutions to calculate the membrane salt rejection. The salt permeability coefficient ($B$) was then calculated by

$$B = \frac{A(1 - R)(\Delta P - \Delta \Pi)}{R}$$

where $\Delta P$ is the hydraulic pressure and $\Delta \Pi$ is the osmotic pressure of the feed solution in the modified RO test.

**Determination of Water Flux and Projected Power Density in the PRO System.** A customized counter-current cross-flow FO test cell (8 cm in length and 4 cm in width) was used to measure the GOM water flux. A silicon pad with a hole (1 cm × 1 cm) in the center was inserted into the test cell to create an effective testing area of 1 cm². A mesh-type spacer was used inside both the feed and draw solution chambers. During the experiment, the feed and draw solutions were pumped into the chambers with a cross-flow velocity of 27.8 cm/s. The weight and concentration change of the feed solution were monitored by a digital balance and a conductivity meter to calculate the water flux and (reverse) salt flux, respectively. The test was run for at least 1 h for each measurement and the average value was calculated.

The water flux was first measured with 1 M NaCl as a draw solution and DI water as a feed solution. To investigate the influence of solution pH on the water and salt transport across the GOM, the pH of the feed and draw solutions was adjusted by adding HCl or NaOH. Next, the water flux was measured by using NaCl and NH₄HCO₃ solutions at different concentrations of 0.5, 1, 1.5, and 2 M as draw solutions with DI water as the feed solution. To evaluate how well the GOM can mitigate the ICP during PRO, NaCl and NH₄HCO₃ solutions (0.1 M) were used as the feed solutions. The corresponding water flux for each draw and feed solution was calculated.

Additionally, the water flux and projected power density for PRO under hydraulic pressure was calculated using equations from previous studies specifically, by considering the effects of ICP, external concentration polarization, and (reverse) salt permeation.
Estimation of System Energy Efficiency. The osmotic heat engine consumes thermal energy to separate the solute from the mixed solution and to generate power by mixing the diluted solution and pressurized concentrated solution. The energy efficiency of the overall system can be expressed as

\[
\eta = \frac{P}{q_{nt}}
\]

where \( \eta \) is the energy efficiency of the osmotic heat engine, \( P \) is the energy generated from the electricity generation stage, and \( q_{nt} \) is the thermal energy consumed to (re)generate the draw and feed solutions. By analysis of the osmotic heat engine process in this study (Figure S3), the energy efficiency can be calculated by

\[
\eta = \frac{W}{\beta J_W (c_d - c_f)}
\]

where \( \beta \) is the specific heat duty of ammonium bicarbonate, \( c_d \) is the concentration of the draw solution, and \( c_f \) is the concentration of the feed solution. Equation 5 indicates that the energy efficiency is independent of the membrane area and operation time. The detailed calculation of the system energy efficiency is shown in the Supporting Information (SI1).

ASSOCIATED CONTENT

Supporting Information
The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acsomega.8b02101.

Energy efficiency of the osmotic heat engine; schematic illustration of the osmotic pressure profiles of different membranes; schematic illustration of the modified RO testing cell; schematic illustration of the osmotic heat engine process; XRD patterns of the dry and wet GOMs; and supplementary information on the power generation of GOM (PDF)

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Notes

The authors declare no competing financial interest.

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