Improving Energy Scavenging Capacity via a Vertically Configured Closed-Circuit PRO System

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Abstract
A novel configuration for a closed-circuit PRO (CPRO) system is described. The CPRO system enables fluid flow in both the draw and feed channels using gravitational potential energy. The new PRO system is designed to store gravitational potential energy derived from input thermal energy for use in fluid circulation, thereby bypassing the need for circulation pumps. As a result the novel PRO system can recover a significant amount of the 66% of energy typically unavailable for external use. The new PRO sys-tem is self-cleaning with all salt (in the draw solution, having leaked through the membrane) washed into the distillation unit. Circulation of distilled water is accomplished using stored gravitational potential energy. Circulation of the saline solution is accomplished using a gravitationally powered volumetric mass transfer process without significant loss of internal pressure. A laboratory test device was constructed and operated. It's top performance is evaluated at a recovery of 67.0% of the energy potential.

Keywords: pressure retarded osmosis, vertical closed circuit pressure retarded osmosis

Introduction

Pressure retarded osmosis (PRO) systems are energy-transforming devices capable of transforming thermal energy into pressurized water using differences in solute concentration of solutions. The resulting pressurized water can then be used to generate power (McGinnis, 2008). This process occurs via a flow of liquid through a semi-permeable barrier through which water or other solvent passes through more readily than salts or other substances that may be dissolved in the solvent (Kaleda, 2011). If the solution on one side of the barrier has a higher dissolved solute concentration than that on the other side of the barrier, solvent moves through the barrier in the direction of the more highly concentrated solution. At the same time, solute moves across the barrier toward the lower concentration solution. Because the rate of movement of solute is much slower than that of solvent, a pressure difference between the two sides may evolve in the relatively short term, enabling work to be done.

Closed-circuit PRO (CPRO) systems are PRO systems in which the high pressure, medium concentration solution moves through a power generator and on into a separator. The separator removes the solvent from the solute by some means, typically through thermal distillation, and returns the two streams of liquid to the membrane assembly (Efraty, 2014 and Alfaee 2012). Such a system can be run virtually indefinitely with no influx of either salt or water. The CPRO system must utilize energy to do the separation; this energy drives the pressurization and whatever work might be undertaken with the pressurized water. A typical use of CPRO systems is transformation of waste, parasitic, or unwanted heat into electrical power: energy scavenging.

In CPRO systems, high pressure solution is used to power circulation pumps that move the high and low concentration solutions from the distiller to the membrane chamber. It is also used to generate electrical power. A ratio of 33% electricity production to 66% circulation pump power is typical for many systems (Hong et. al, 2013). The use of two thirds of the energy potential in internal operation is a strong limiting design element of the system.

The built world consists of a myriad of opportunities for energy scavenging in cases where the thermal gradient one has to work with is of the order of $10 - 20^{\circ}C$ (Air Vent, 2014). Structures such as sheds, attics, and others can routinely generate relatively small thermal gradients that themselves represent a significant amount of energy opportunity. Capturing this energy could enable low energy devices that could provide communication, sensor activation, and other low wattage opportunities that might be useful in remote areas or in the wake of a calamity.

If CRPO systems are to be used for energy acquisition, it is desirable to use systems with superior energy recovery to that of conventional CPRO system. Reducing the internal power utilization of the device enhances the amount of energy available for external use. This paper presents work we've done on a vertically oriented CPRO system (VCPRO) which reduces the energy expenditures due to pumping through pressure pumps and thereby enhances the amount of energy that can be delivered.

The remainder of the paper is organized as follows. Section 2 describes the system and provides a theoretical analysis of its performance characteristics. Section 3 describes the experiments undertaken with the system and provides their experimental data. Section 4 gives a discussion of the system, experimental designs, and potential future improvements to the system. Section 5 concludes.

Enhancing recovered energy using a vertical layout for a CPRO System

A typical CPRO system involves four principle parts: a means of separating solvent from solution (typically a distiller), a membrane assembly, a generator, and one or more pressure pumps capable of using high pressure to drive the circulation of the draw solution and the distilled solvent. In general, the power required to carry out the circulation of the draw solution and the feed solution (distillate) is drawn off of the pressurized and diluted draw solution downstream from the membrane assembly. This limits the overall power that can be harvested.

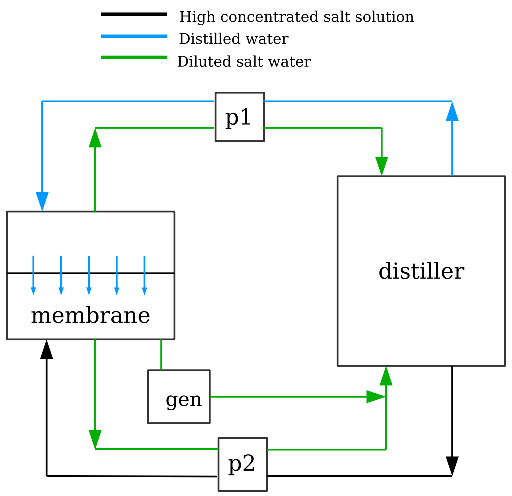


Figure 2.1: The horizontal arrangement of the CPRO.

The vertically oriented CPRO system (VCPRO)

We developed an alternative organization for the CPRO system in which the parts of the system are laid out vertically, as in Figure 2.2. This system eliminates the need for pressure pumps using a system of valves, conduits, and vertical drops to circulate the different water sources.

General Design Strategy

In energy harvesting, some form of relatively low concentration untapped energy is acquired and transformed to another form that is easily usable (Miller, 2006). In our system, the energy we are interested in acquiring is thermal energy. While the transformation of this energy into a usable form is expected to yield a small return for scavenged energy due to the low temperature gradients generally available and the concomitant thermodynamic limitations[1] , improvements in distillation technology (which are not an explicit goal of this study) can be used to increase the recovered energy significantly.

The VCPRO system recovers energy by using thermal energy and relatively small thermal gradients to distill water. This water moves as vapor up a gravitational potential, acquiring gravitational potential energy. The water then condenses and is collected in a water reservoir, with excess water (beyond the reservoir's capacity) continuing on into a membrane assembly. The brine is retained by the distiller. The membrane assembly contains two chambers in contact across an osmosis membrane. The brine is used to fill one chamber while the distillate fills the other chamber. As a result of the differing concentrations, the brine is pressurized as the distillate moves via forward osmosis through the membrane. The pressurized fluid flows from the membrane assembly to a generator where it can be used to generate electrical power. The fluid then flows back into the distiller. Periodically the water retained in the reservoir is released into the distilled water side of the membrane assembly, forcing the water already there out into the distiller. This cleans the distilled water side of the membrane and recovers the salt that has flowed through the membrane. The cycle continues as long as a thermal gradient at the distiller side is maintained.

Detailed Description

Our distiller comprises two principle parts: an evaporator (1) and a condenser (9). The evaporator is an acrylic vertically elongated chamber principally made from two coaxial acrylic tubes, closed at both ends. A vacuum is retained between the two tubes, insulating the two from one-another. Heat is absorbed through a copper tube attached to the bottom of the inner acrylic tube. Vapor generated as the water evaporates, fills the distiller, and travels to the condenser, which is located between the evaporater (1) and the reservoir (3). In our laboratory model, the condenser (9) is a long copper tube.

The distiller is directly connected to three other parts of the apparatus: the reservoir (3), the generator (2), and the membrane assembly (6) through a set of valves. Liquid enters the distiller from two of these three sources and leaves the distiller as vapor and distilled water. Liquid entering the distiller from the generator (2) comes through the top of the evaporator (1) while liquid from the membrane assembly's inner chamber (4) enters through the side of the evaporator (1). The distiller is connected to the membrane assembly's outer chamber (5) via valves V6 and V7 connected to two locations at the bottom of the evaporator (1). These valves can be used to transfer dilute water from the outer membrane assembly chamber to the distiller using a mass transfer process driven by the relative densities of the liquids in the membrane assembly and the evaporator. One connection from the outer chamber of the membrane assembly (5) to the evaporator (1) is

[1] i.e. Carnot efficiency limitations

connected to an internal tube that extends partway into the evaporator. When the valves V6 and V7 are opened, the heavier concentrated water in the evaporator can displace the lighter liquid in the membrane assembly's outer chamber, restoring the draw solution to a high concentration.

The reservoir (3) accepts water from the condenser and stores it. Beyond a maximum capacity, additional water deposited in the reservoir flows through to the connecting tubing joining the reservoir and the membrane assembly. The valve at the bottom of the reservoir (V2) can be opened to drain the reservoir. Both pathways bring distilled water into the membrane assembly's inner chamber (4). If the reservoir and the connecting tubing are sufficiently full of water, draining the reservoir deposits water into the distiller through valves V2, V3, V4, and V8. This effectively "cleans" this side of the membrane and recovers salt that may have passed through the membrane into the inner chamber.

The membrane assembly (6) comprises two chambers defined by two coaxial acrylic cylinders. Accordingly, these are an inner chamber (4) and an outer chamber (5). The two are separated by a cylindrical cellulose acetate membrane[2] supported by the inner acrylic cylinder. The inner chamber contains a low concentration solution derived from distilled water; the outer chamber is filled with a draw solution (NaCl solution, in this study). The top of the inner chamber has a port which can be connected to the output of the reservoir. The bottom of the inner chamber is connected to the side of the evaporator (1) through valves V8 and V3. Distilled water can flow freely through the interior chamber from valve V4 to valve V8. The outer chamber (5) is connected to the collector (7) and the generator (2) through valve V5 and the pressure relief valve (8). It is also connected to the evaporator (1) through valves V6 and V7, as described above; these valves are vertically separated with one near the top of the outer chamber (5) and the other near the bottom. Pressurized water flows through valve V5 and on through the pressure relief valve (8) before continuing on to the generator (2). In our study, the generator is bypassed.

(8) is a one-way pressure relief valve which opens at a pressure differential of 33.9 kPa. Water pumped through the valve may be measured at the collector (7), providing a measure of the amount of available energy at this point. Subsequent models will eliminate this pressure valve, utilizing the power generator (2). Water pumped through this valve is drained back into the distiller from the top of the evaporator (1).

Water flowing through the membrane dilutes the solution in the membrane assembly's outer chamber. As a result, it is necessary to periodically restore its concentration. This is accomplished by opening the two valves (V6 and V7) on the side. This step reduces the pressure in the membrane assemby's external chamber, but maintains the pressure between the membrane assembly and the generator; normal flow will be restored when the pressure within the membrane assembly is restored. As the diluted water is less dense than the solution in the distiller, it is relatively bouyant and is displaced by the heavier and more concentrated brine

[2]We obtained cellulose acetate membrane material from standard GE modules, model TFM-18.

that results from utilizing the distiller. This restores the concentration of the draw solution and the functionality of the device.

Salt passes through the membrane into the membrane assembly's inner chamber. The solution therein becomes increasingly saline over time. It is necessary to wash out the inner chamber periodically. This is accomplished by opening V3, V4, V8, and V2. The water in the reservoir naturally drains through the membrane assembly and into the distiller due to its height. The process washes out salt in the membrane assembly's internal chamber and recovers it in the distiller.

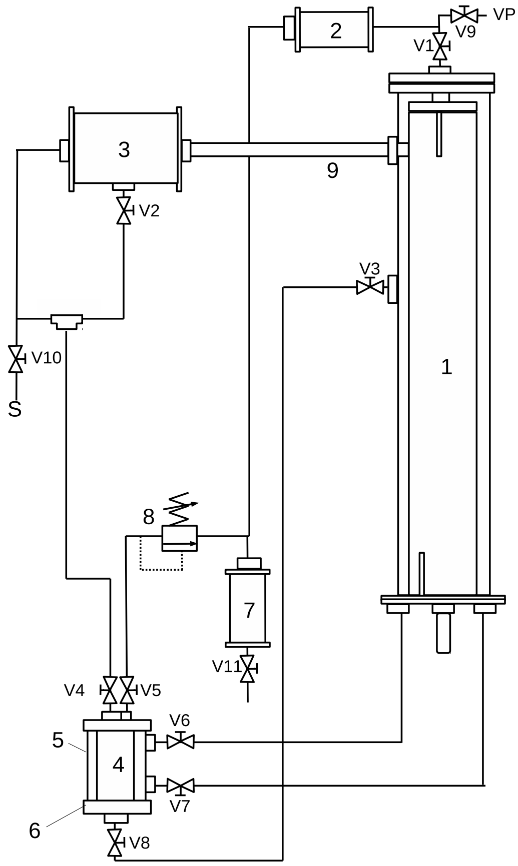


Figure 2.2: The vertical arrangement of the CPRO. The vertical CPRO consists of four principle parts: (1 and 9) the distiller, (2) power generator, (3) the reservoir, and (6) the membrane assembly.

In this figure, the evaporator (1) is vertically elongated, enabling the vapor from the first of what can be several stages to travel vertically prior to condensation. The energy may then be used for subsequent stages in complex distillation processes. In our laboratory scale device, the vertical lift is limited. However, in larger devices the vertical lift desired can be significant.

Reduced Carnot efficiency due to vertical orientation

In order to reduce the thermal energy required to pre-heat the distiller so as to begin distilling water, the entire distiller is evacuated and the rarified atmosphere is replaced with water vapor using a steam injection procedure. This effectively transforms the distiller into a heat pipe[3]. As a result, the transfer of thermal energy is extremely fast and requires no priming. The vertical height of the distiller affects the pressure (and therefore temperature) differential between the elevated condenser and the distiller; the Carnot efficiency is necessarily reduced as a result of the height related temperature difference.

In order to determine the scale of the temperature difference, we can model the column of vapor as incompressible gas of density ρ_g. In this case, the pressure exerted by the column of gas is given by

$$P_c = \rho_g g h. \tag{1}$$

As a result, if the temperature at the bottom of the column is given by T_h, the temperature at the top of the column is given by Antoine's equation as

$$P_t = e^{\left(A - \frac{B}{C+T_h}\right)} - \rho_g g h. \tag{2}$$

where A, B, and C, are experimentally determined constants. Therefore, the temperature at the top of the column will have cooled to

$$T_h^{'} = \frac{B}{A - log\left(e^{\left(A - \frac{B}{C+T_h}\right)} - \rho_g g h\right)} - C.$$

The resulting Carnot efficiency is limited by $e = \frac{T_h^{'} - T_l}{T_l}$.

Overall energy efficiency

We can model the function of the distiller as follows. Given a quantity of heat ΔQ_{in}, a quantity of water ΔV_{in} is generated. This is given by

$$\Delta V_{in} = \kappa \frac{\Delta Q_{in}}{H_v\left(T, M\right)} \tag{3}$$

where $H_v\left(T, M\right)$ is the heat of vaporization of water at the temperature and molarity[4], and κ is a proportionality constant which captures the efficiency and the multiplicative effect of the distiller. For a single stage system, this is necessarily lower than 1. For more complex systems, such as multi-effect distillation MED systems, this can be significantly higher than 1[5].

Of the water that is generated by the distiller, some proportion of it is used to clean the system while the remaining water may be used to clean the membrane's inner

[3]A *heat pipe* is also known as a *Perkin's tube*.

[4]The heat of vaporization can be viewed as essentially constant, despite the elevated molarity, if the heat of vaporization as a function of mass refers only to the mass of the water being evaporated rather than as a function of the mass of the entire quantity of water and salt contained therein.[**?**]

[5]Values of κ of up to 23 have been reported, though at high temperature[**?**, **?**].

chamber. The frequency of cleaning depends on the concentration of the external solution, the operating pressures and temperatures, and the kind of membrane being used. Based on these characteristics, we can determine the proportion of water χ used for washing the membrane interior and the proportion of water $(1-\chi)$ of water used for power production.

The distilled water is deposited in the membrane chamber where it passes through the membrane by forward osmosis, generating a stream of water pressurized to a pressure

$$P_{out} \leq \pi = iRMT. \tag{4}$$

Here M denotes the molarity of the water on the other side of the membrane, R is the gas constant, i is the Van t'Hoff factor, π is the osmotic pressure, and T is the temperature. The amount of energy in the stream is equal to

$$E_{out} = \Delta V_{in} P_{out} (1-\xi) \leq \Delta V_{in} i (1-\xi) RMT = \kappa \frac{\Delta Q_{in} i (1-\xi) RMT}{H_v(T)}. \tag{5}$$

The rate of water pumping may be obtained using

$$J_w = A(\pi - \Delta P) \tag{6}$$

where A is the membrane surface area and ΔP is the pressure difference between the sides of the membrane. $J_w = \frac{dV_{out}}{dt}$. As $\frac{dV_{out}}{dt} \leq \frac{dV_{in}}{dt}$,

$$\frac{dE_{out}}{dt} = \frac{dV_{out}}{dt} P_{out} \leq \frac{dV_{in}}{dt} P_{out} = \kappa \frac{i(1-\xi) RMT}{H_v(T)} \frac{dQ_{in}}{dt}. \tag{7}$$

We can rate the amount of output power as the ratio of the amount of power recovered and the maximum amount of power recovered

$$e = 1 - \xi. \tag{8}$$

Experimental Procedures

We constructed and operated a laboratory scale model consisting of the primary structures described above in Section 2.1. Referring to Figure 2.2, we describe here the procedures used during the evaluation of the VCPRO system.

Preparation

This procedure is used to prepare the device with an internal wet vacuum, enhancing the distillation process. The evaporator (1) was initially filled with saturated NaCl solution, the internal chamber of the membrane assembly (4) was filled with distilled water, and the external chamber of the membrane assembly (5) was filled with solution drained from the evaporator (1). A vacuum pump connected to valve V9 evacuated the air within the system whilst steam was injected from the hot water reservoir connected to valve V10 in order to force out any remaining air that otherwise would not have been evacuated. While the vacuum pump was on, only V11 was closed. Once the pump was turned off, valves V2, V3, V6, V7, V8, V9, V10, and V11 were closed and steam injection was ceased.

Distillation/Pressurization/Work

The copper tube connected to the bottom of the evaporator (1) was heated to a temperture of ambient plus $16 - 20^{\circ}C$, which, in turn, heated the saline solution in the evaporator (1) and caused water to evaporate. The water condensed in the copper pipe (9) and traveled through it to the reservoir (3). Water additionally condensed in the tubing leading to the membrane assembly (6). The water that entered the membrane assembly did so through its inner chamber (4). There was a net movement of water across the osmosis membrane from the inner chamber (4) to the outer chamber (5). Pressure forced saline solution from the membrane assembly (6) to the evaporator (1). Valves V1 and V5 were open, and valves V2, V3, V4, V6, V7, and V8 were closed.

The pressure generated by the osmotic action in the membrane chamber (6) was measured by the pressure relief valve (8) which required a minimum pressure of 33.9 kPa to open. Work was estimated by calculating the product of the pressure required to open the valve and the volume of water that passed through the valve and was collected in the collector (7).

"Recharge"

This procedure exchanges the locations of the solutions in the outer chamber of the membrane assembly (5) and the evaporator (1), taking advantage of their relative densities. By closing valve V5 and opening valves V6 and V7, we connected the evaporator (1) and the outer chamber of the membrane assembly (5). The heavier and more concentrated saline solution of the evaporator (1) moves through the tubing and displaces the lighter and less concentrated solution in the outer chamber of the membrane assembly (5). Simultaneously, the lighter and less concentrated solution of the outer chamber of the membrane assembly (5) traveled through the tubing to the evaporator (1), filling the volume vacated by the more concentrated solution. This process is a natural result of gravitational action and requires no external intervention. The completion of this process restores the concentration gradient across the membrane.

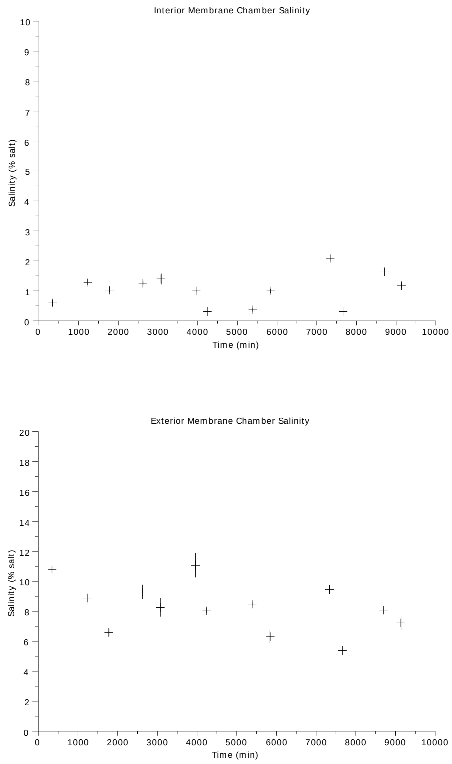
Cleaning

This procedure is necessary to clean the slightly saline solution that results on the "clean" side of the osmosis membrane from the movement of salt through the membrane. In this procedure, valves V2, V3, and V8 are opened. The distilled water in the reservoir (2) drains into the inner chamber of the membrane assembly (4), through valves V3 and V8 and their connecting tubing, and into the evaporator (1). This effectively washes the slightly salty solution out of the inner chamber of the membrane assembly (4) and recovers the salt in the evaporator (1). After the procedure is completed, valves V2, V3, and V8 are closed.

Data and analysis

Salinity measures

We measured the salinity of both the interior and exterior chambers of the membrane assembly. During the experimental run, a collecting chamber was added to the exterior membrane chamber, allowing the pressurized water to be collected. Every 10 hours, we released the vacuum and measured the volume of solution that had pooled in the collector. We also drained just enough distilled water from the interior of the membrane chamber to measure its salinity. The salinity of each sample was measured three or four times with a salinity probe[6].



(A) (B)

Figure 4.1: The variation of the salinities in the internal chamber (A) and external chamber (B) of the membrane assembly during a one-week operational run.

The data thus obtained are given in Figure 4.1 Notably, the variation of the salinities is limited, and the salinities vary around a relatively constant set point over a nearly one-week period.

Power Output

We measured the pressure of the external membrane chamber and the pumping volume during the same period. These data are depicted in Figure 4.2.

[6] We used a model CDH45 salinity probe manufactured by Omega.

(A) (B)

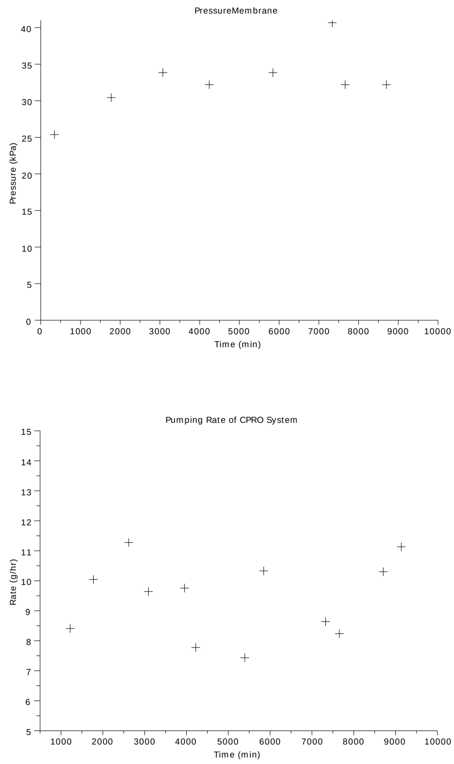


Figure 4.2: The system pressure (A) and the pumping rate (B) during a one-week operational run of the VCPRO system.

These data can be combined to determine the power output of the VCPRO system. The power output is depicted in Figure 4.3.

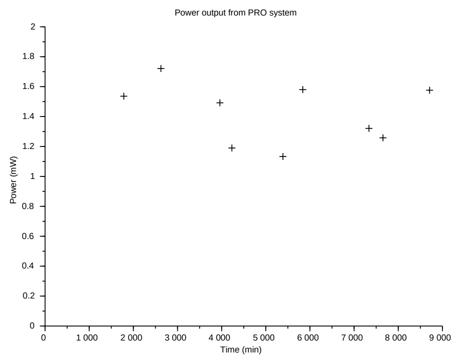


Figure 4.3: The power output of the VCPRO system during a one-week operational run.

Notably, the power output varies around a relatively constant output averaging $1.48 \pm 0.28\ mW$.

A pressure relief valve was used to regulate the internal pressure in the place of the generator. This allowed the system to pressurize as it might while using a generator.

Efficiency measures

There are two distinct areas of efficiency in this device. The first area of efficiency results from the generation of water from the input heat. A thermal, one-stage distillation device has a maximal water output of

$$V_{max} = \gamma \frac{\Delta E}{H_v} \tag{9}$$

given an energy input of ΔE and an efficiency coefficient of γ. In our laboratory model, we measured our efficiency as 0.52 ± 0.012. As a result, we report our efficiencies as a ratio of the measured distillation conversion to the maximum in equation (9).

The overall efficiency of the device is the ratio of the energy in to the energy out. In our device, we input $15W$ and produced approximately 1.48 ± 0.035 mW. This gives an efficiency of $9.87 \times 10^{-3}\%$. Since the Carnot efficiency is limited to 6.49%, this represents a corrected efficiency of the PRO system alone of 0.152%.

When we compare our system, which was limited to a total pressure of $33kPa$ to the maximal energy output given by $i\Delta MRT\Delta V$, we find that our system produced $9.42 \pm 0.236\%$ of the maximal total energy possible.

Discussion

The goal of the VCPRO system is to enable the acquisition of an increased portion of energy generated through the osmotic process through the elimination of the power consumption of the pumping systems. This is possible through the creation of an alternative circulation process in which graviational potential energy is used in lieu of internally generated energy. As a result, the increased energy output is limited by $1 - \xi$, as given in (8).

Our experimental analysis of the device centered around the creation of sustainable operating conditions within the device. As our data indicates, the internal conditions surrounding the membrane, the inner and outer chamber concentrations, the pressures in these chambers, and the power output, were all consistent. In particular, the values of these measurables varied around a stable point, generating time-based variations with a flat trendline. As a result, we infer that the operation of the VCPRO system is stable and can output energy on a continual basis.

Our system utilized a custom pressure relief valve which enabled liquid flow at high pressures. The pressure relief opened at a pressure of approximately 33 kPa. This is well below the theoretical maximum pressure of the system given the saline concentrations on either side of the membrane. This pressure was chosen so as to ensure that the membrane and membrane chamber remained intact. As the chamber itself is constructed from acrylic pieces fused together with acrylic cement or epoxy and the membrane is not rated for high pressure, we chose to limit the pressure during these runs. More robust membrane chambers and membranes would enable higher pressures and therefore greater energy generation.

During our test of the VCPRO system, we recharged the system and cleaned the system two times daily during the first half of the run and then reduced that to once daily during the second part of the run. As can be seen in Figure 4.1, a slight change in the concentrations inside and outside the membrane result as compared to earlier in the run. Despite this, our device continued to pump pressurized water at a power rating averaging $1.48 \pm 0.28\ mW$ throughout the run. This rate of generation of pressurized water was too small to utilize for electrical power generation; a subsequent study may utilize pooling to enable power generation.

The number of recharge cycles can be used to estimate the amount of water used for recharging as compared to the amount pumped. The amount of water pumped per day is approximately 240 $\frac{mL}{day}$. Each recharge cycle consumed approximately 118.2 mL. As a result, cleaning our system twice daily produced a yield of 50.4% while lowering the cleaning cycle to once daily produced a yield of 67.0%. As this number is a function of the salt flux through the membrane, it is expected that lower salt fluxes will produce higher energy yields resulting from longer pumping periods between cleaning events.

The increase of energy recovery of our VCPRO system more than doubles the reported yields of systems employed elsewhere commercially or academically. Though our yields are quite low for systems employing single-stage distillers, the system is simple, employs few moving parts (excluding the generator), and can passively generate power based on low temperature gradients. Since thermal gradients of this magnitude exist in many structures in the built world including homes, storage facilities, and office buildings, the potential for its use as a secondary, nearly passive source of power is reasonable. The system described here is not likely to require frequent maintenance, making it suitable for use in the developing or developed world.

Conclusions

This paper describes a novel closed pressure retarded osmosis (CPRO) device. The current device is novel in that its vertical configuration removes the need for pressure pumps that generally absorb a significant amount of energy in a standard pressure retarded osmosis (PRO) system or a CPRO system. We described here the implementation of a laboratory scale vertical closed pressure retarded osmosis system (VCPRO). In our laboratory scale device, regeneration of brine concentration after dilution by effluent is accomplished using gravitational cycling. Cleaning of the feed solution is similarly accomplished using gravitational cycling. These two procedures maintain the concentration gradient across the membrane, enabling continued operation. The brine and distilled water sources are regenerated in the distiller which itself is driven by thermal gradients not exceeding $30^{\circ}C$. These thermal gradients may be routinely found in much of the built world, indicating that there is a significant potential for energy scavenging using this and related systems.

This device operates with two unusual conditions. First, the membrane has saline water on one side and distilled water on the other side. The use of distilled water operating in a forward osmosis process is likely to extend the operating lifetime of the membrane to as many as twenty years (Desormeaux, 2014). At the same time, the device is operated at relatively low pressure on the distilled water side. This low pressure is an inhibiting factor for bacterial growth, and serves to limit fouling of the membrane. As a result of these two conditions, this device is a good choice for use in areas where replacement parts might be unavailable or infeasible. In particular, we believe that this device is a good choice for use in the developing world where replacement parts may be difficult or impossible to obtain.

We have not integrated an electrical power generator in the current system; we shall do so in the future so as to evaluate the theoretical and actual electrical power yields of the system. The new system will include a much larger membrane surface so as to enable a large flow rate under pressure. Future studies of this system will also include the integration of the system in a built structure, such as a shed or an attic. It is expected that the thermal gradients between such a structure and the outside world may exceed fifteen degrees resulting in a continual and permanent source of electricity.

Acknowledgments

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