

COMPACT SINGLE MULTISTAGE DISTILLATION

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ABSTRACT

We report the design and function of a distillation apparatus which uses salt concentration gradients to drive distillation and desalination of simulated sea water. Utilizing the entrochemical effect, the system generates an internal thermal gradient. An internal distiller is arranged with the condenser in the cold end of the entrochemical system and a seawater reservoir in the warm end of the entrochemical system. The heat of vaporization is recaptured in the cold side of the entrochemical system and re-used. The spent solution in the entrochemical system can be recharged using evaporation, making the surrounding thermal energy the source of energy that powers the system.

We utilize two draw solutions, one made from food grade anhydrous CaCl_2 and tap water and the other made from a saturated $\text{NaCl} / \text{MgSO}_4 / \text{KNO}_3$ (NMK) solution from food grade NaCl and MgSO_4 , industrial grade KNO_3 , and tap water. These solutions are utilized in the entrochemical distiller. As the operational temperature increases the CaCl_2 -based distiller exhibits an increasing volumetric efficiency, varying from 30.9% to 83.1%; the maximum volumetric efficiency of the NMK-based distiller is found to be 60.42%. Since evaporative recharge is also spontaneous for diluted NMK solution and diluted CaCl_2 solution, the overall process represents a scalable distillation process driven largely by environmental thermal energy, independent of complex or expensive materials, and capable of being implemented in areas with extremely limited technical capabilities.

KEYWORDS

entrochemical system, distillation, heat of vaporization

INTRODUCTION

Despite intense research, desalination remains a difficult problem, owing primarily to the high heat of vaporization of water and to the complexity of filtration-based solutions to desalination (Isaka, 2013). Higher energy thermal methods such as multieffect distillation (MED) require energy sources that are cheap to acquire, simple to employ, and clean (Clayton, 2015; Blomquist, 2003; Davis, 2006). At present, fulfilling all of these requirements is a challenge. are designed to reuse the heat of vaporization whenever possible to enable the same thermal energy to generate more clean water than could be produced using a single stage alone. This is achieved by heating the water from one stage with condensing steam from a prior stage. Energetic costs of clean water using this method can be as low as 2 kWh per m^3 .

The other major method in use today is filtration (Clayton, 2015; Fritzmann, 2007; Camacho, 2013). Filtration is dominated today by the use of reverse osmosis in which high pressure water is pumped through an osmosis filter which selectively passes water at quicker rates than many dissolved substances. This is a complex process involving the creation of high temperature and pressure water and energy recapture on the clean water side. Significant technical challenges exist around membrane fouling, chemical pretreatment, and other processes related to osmosis. Current energy expenditures range from 3 to 10 kWh per m^3 of water (Camacho, 2013).

In all cases described above, the energetic input of the system comes from either fossil fuel-derived power or renewable thermal or electrical sources. In order to generate significant amounts of energy, either high temperature or high pressure must be employed. In recent years, however, a new technological innovation based on absorption refrigeration (Srikhirin, 2001; Lowenstein, 2006) has emerged. The systems known as entrochemical systems (Kazadi, 2015a; Kazadi, 2013) employ an internal entropy transfer to generate and maintain an internal thermal gradient. The system can be recharged using a passive evaporative process which can be enhanced using a solar chimney (Kazadi, 2015b). The thermal gradient is actively maintained through an internal water transfer between at least two parts of the system. The system consumes water, which need not be potable, and emits water vapor.

In this paper, we demonstrate how distillation can be achieved using a distiller driven by an entrocchemical process. Such a system acquires its ability to function from work done by the environment on a dilute saline solution used in the thermal gradient process, causing it to become more concentrated. As a result, it can be viewed as being powered by environmental heat. We describe the design, function, and performance of an entrocchemical distiller in a variety of ambient thermal environments which represent several thermal environments that either exist naturally or could exist in purely solar thermally heated enclosed spaces.

DESIGN AND THEORY OF OPERATION OF THE ENTROCHEMICAL DISTILLER

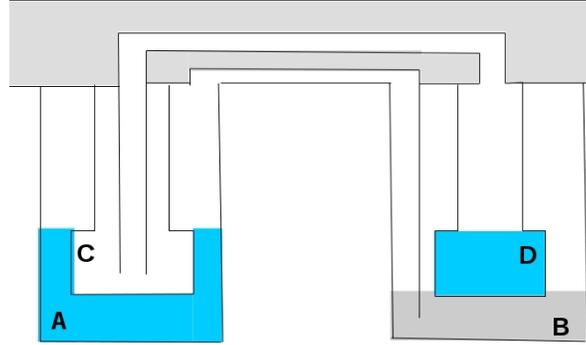


Figure 2.1: The entrocchemical distiller.

The entrocchemical distiller is depicted in Figure 2.1. The device comprises two large outer chambers enclosing two smaller inner chambers. The large outer chambers are connected to one-another via a passageway between them and are designated chamber A and B. The passageway ends in the ceiling of chamber A and at the end of a vertical tube in chamber B. The smaller inner chambers designated C and D are connected to one-another via a separate passageway which ends in the ceiling of each chamber. Chamber C is located within chamber A while D is located within chamber B. A simulated seawater solution of 0.5 molar NaCl is placed in chambers A and D while either a saturated CaCl_2 solution⁴ or a saturated NaCl / MgSO_4 / KNO_3 (NMK) ²-solution is placed in chamber B. The tube in chamber B that terminates the passageway from chamber A ends below the surface of the concentrated solution in chamber B. A wet vacuum is created within all four chambers, initiating the distillation.

We constructed a bench-level device with internal water reservoirs of 110 mL and external water reservoirs of approximately 1000 mL. The external reservoirs are constructed from 4 inch diameter acrylic pipe with a 0.25 inch wall. The internal reservoirs are constructed from stainless steel with a 0.003 mil thickness. The pathways and connecting structures are constructed from acrylic plating and sealed with nitrile o-rings and vacuum grease.

As demonstrated elsewhere, entrocchemical devices generate internal thermal gradients between solutions of differing concentration when they are coupled via a pathway filled, primarily, with the vapor from the solvent being used. This happens because the differing solutions have differing equilibrium vapor pressures. One solution reacts to the contained pressure by evaporating water to increase the pressure while the other absorbs it, reducing the pressure. This transfers thermal energy between the reservoirs, and a thermal gradient results.

In our system, the simulated saltwater in chamber A begins boiling when the wet vacuum is established. Vapor from the saltwater travels to the concentrated solution via the passageway, emerging as a result of the differing concentration of dissolved substances found in separate water solutions. The thermal gradient develops as a result of movement of water from the simulated saltwater to the concentrated solution, which also transfers the heat of vaporization. We may estimate how much of the heat of vaporization is transferred as sensible heat³.

$$\frac{1}{\ln\left(\frac{m_h}{V}\right)} \left(H_v \Delta V - RT \ln \left(1 - \frac{\Delta V}{V_h + \Delta V} \right) \right) = \Delta T_h \quad (1)$$

and

$$\frac{-1}{\ln\left(\frac{m_l}{V}\right)}\left(H_v\Delta V - RT\ln\left(1 - \frac{\Delta V}{V_l}\right)\right) = \Delta T_l \quad (2)$$

where H_v is the volumetric heat of vaporization, R is the gas constant, T is the temperature, V is the solution volume, and m is the mole ratio of water in solution (subscripts h and l refer to high and low concentration, respectively).

This heat, once it is delivered from the cold reservoir to the warm reservoir, can become a driver of distillation. The entire sensible heat may be deposited into the simulated sea water, leading to its distillation. The heat carried by water vapor from chamber D to chamber C is deposited, upon condensation, into the wall of chamber C. It is transmitted through the wall into Chamber A and drives a second cycle. The entire energetic cycle is illustrated in Figure 2.2.

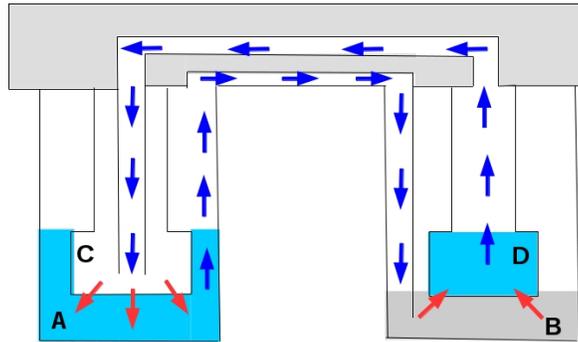


Figure 2.2: The Energy Cycle In The Entrochemical Distiller.

As a result, the distiller acts like a multi-effect distiller despite physically having a single effect. Moreover, as the distillation proceeds, the entire device is apt to cool off due to an increase in the enclosed entropy overall. As it does, heat is replenished from its surrounding reservoir; environmental heat ultimately drives the system.

SYSTEM PERFORMANCE

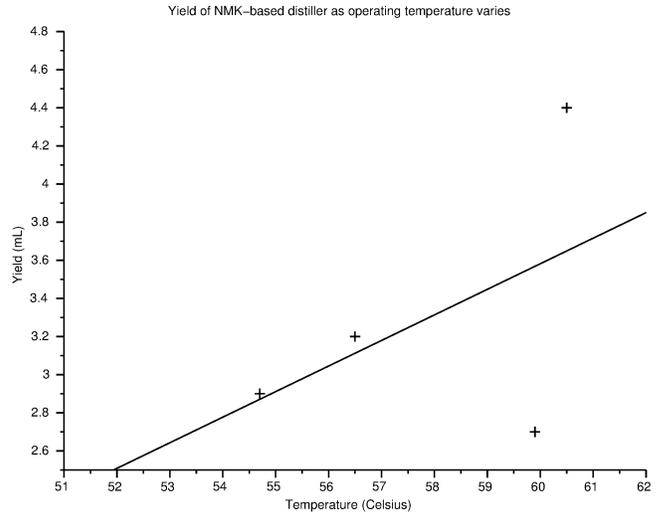
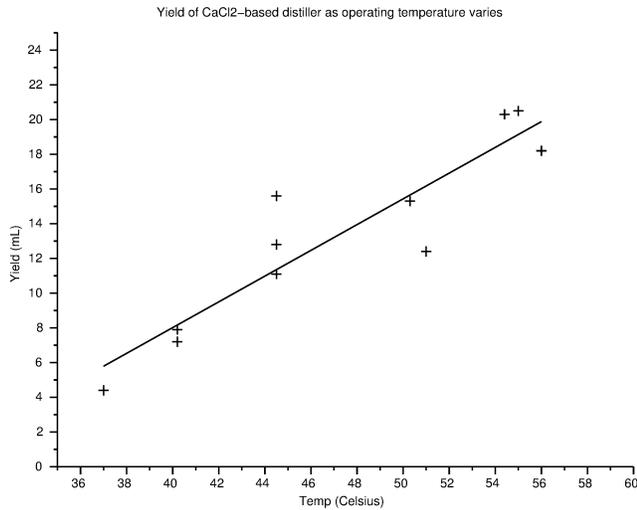
We tested our distiller at a variety of different operating temperatures and with the two solutions indicated in Section 2, a saturated CaCl_2 solution (at 25°C) and a saturated $\text{NaCl}/\text{MgSO}_4/\text{KNO}_3$ solution (at 25°C). We limited these temperatures to a range between 35°C and 60°C . This Section describes our procedure and data

Experimental procedure

During each test, the distiller is prepared in the same way. Chamber 1 is filled with 200 mL of tap water or simulated sea water. Chamber 2 is filled with 60 mL of saturated solution. 25 mL of tap water or simulated sea water is placed in the Chamber 4, and Chamber 3 is left empty. The entire apparatus is placed in the oven and allowed to equilibrate to the new operational temperature for twenty (20) minutes. Once this period elapses, water vapor at 54°C is used to create a wet vacuum in each chamber, with mild vacuum applied for a period of thirty (30) seconds. The apparatus is again placed in the oven and allowed to operate for a period of thirty (30) minutes. At the end of thirty minutes, the amount of liquid in each chamber is weighed.

Experimental results

Figure 3.1 illustrates the yield in mL as a function of temperature. As we initially placed only 25 mL in the distiller there was an artificial maximum yield that the distiller could produce.



(A)

(B)

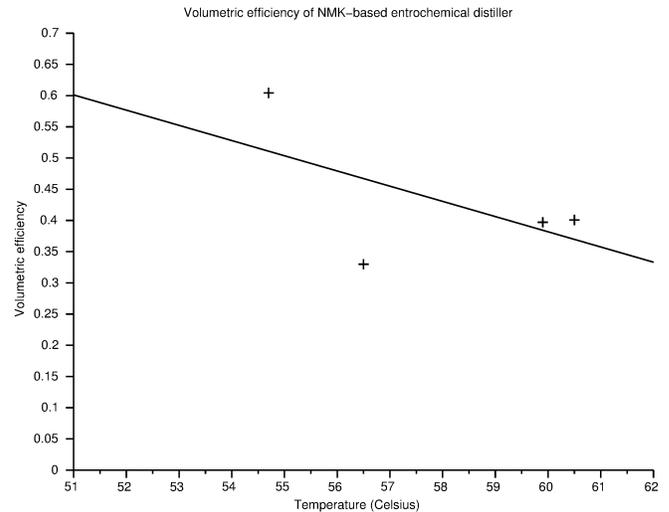
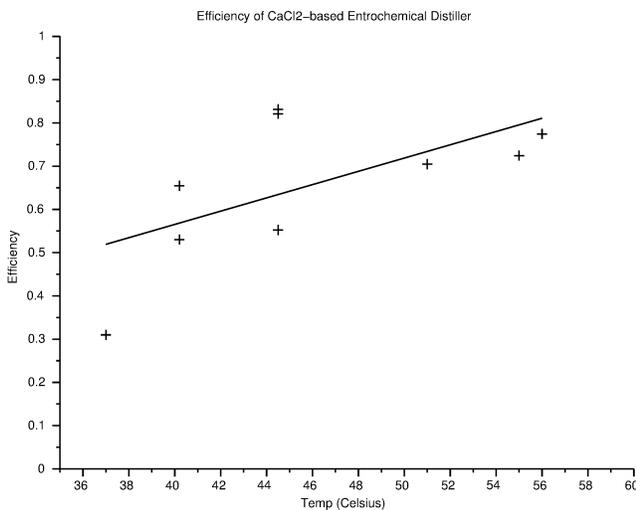
Figure 3.1: This figure gives the distiller yield as the temperature varies when CaCl_2 is used as a draw solution (A), and when the NMK solution is used as a draw solution (B).

As the temperature increases, the distiller yield also increases. While the absolute yield and rate of increase in yield of the distiller varies with the draw solution, the distiller, using either draw solution, is able to generate distilled water. By itself, the yield doesn't indicate the efficiency of the distiller. We can define the distiller *volumetric efficiency* as

$$e = \frac{w_d}{w_t} \quad (3)$$

where w_d is the quantity of water distilled and w_t is the quantity of water transferred from the outer less concentrated water pool to the more concentrated pool. This has 1 as an upper limit, though it is impossible to reach 1 due to entropic losses.

We graph the efficiency data in Figure 3.2 below.



(A)

(B)

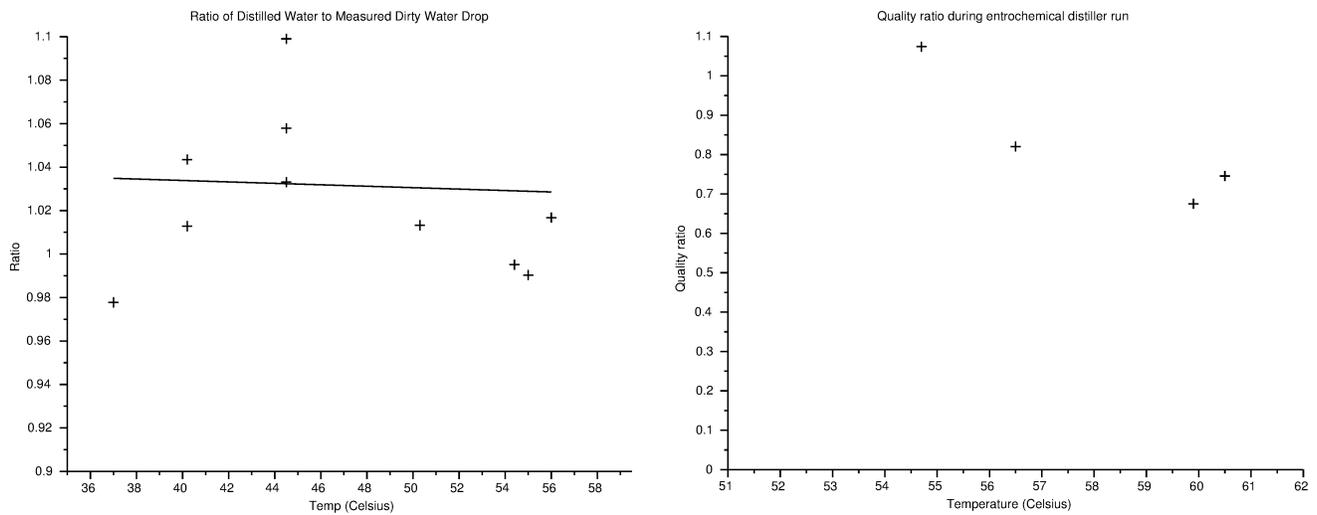
Figure 3.2: The efficiency of the entrochemical distiller as a function of temperature for a CaCl_2 draw solution (A) and for a NMK draw solution (B).

It is clear that as the temperature increases, the efficiency of the CaCl_2 -based distiller increases from 30% to more than 80%, while that of the NMK-based distiller actually seems to decrease.

Analysis

One of the immediate questions that emerge when examining the data is why the volumetric efficiencies seem to increase as the temperature increases with the CaCl_2 -based distiller but seems to do the opposite with the NaCl-based distiller. This seems to happen despite similar increases in the yield of the system as a function of temperature.

One indicator of possible experimental difficulties is the ratio of water distilled to water lost in the distiller. Theoretically, these ratios should be 1, as the amount of water lost should equal that gained. This is largely the case for the CaCl_2 -based distiller as can be seen in Figure 3.3 (A). Yet when similar values are calculated for the NMK-based distiller (Figure 3.3 (B)), the values only approximate 1 for one measurement. This measurement corresponds to a volumetric efficiency of 60.42%, which is similar to midrange values for the CaCl_2 -based distiller. While significantly more data is needed to reach a conclusion, this raises the possibility that the performance of the NMK-based distiller, absent experimental difficulties, is similar in its volumetric efficiency to the CaCl_2 -based distiller.



(A)

(B)

Figure 3.3: The ratio of distilled water collected to the water lost in Chamber D of the distiller for a CaCl_2 draw solution (A) and for a NMK draw solution (B).

COMPLETING THE CYCLE

The entrochemical distiller has two operational cycles which define whether it is part of a system consuming energy or part of a system harvesting energy. The closed energetic cycle results from entrochemical distillers that are physically closed and so retain all of their water and salt. Open energetic cycles result from entrochemical distillers that are physically open or quasi-open and so receive and emit water.

Closed energetic cycle: The closed energetic cycle is depicted below in figure 4.1.

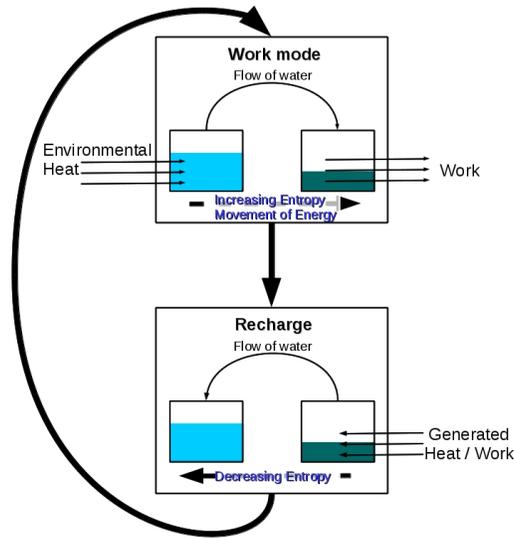


Figure 4.1: The closed energetic cycle for the distiller.

In step one, the distiller functions via the movement of heat back and forth between the hot and cold chambers. As entropy is increasing, the entire device will cool down and the cool side will tend to absorb heat from the surroundings. This heat energy maintains the system's functionality.

The next part of the cycle involves the drying of the dilute draw solution. This is achieved by using thermal or mechanical methods to remove water from the solution. Examples include vacuum distillation, reverse osmosis, or thermal distillation. The water that is removed is recovered and cycled back into the system. This is the *closed* configuration. This configuration generates clean water in the drying stage and generates an additional quantity of water in the next cycle, effectively increasing the output given any energetic input. This configuration is depicted in Figure 4.1.

Note that systems which use energetic processes to generate clean water and in the process produce brine may enhance their water output by using the brine in the entrochemical distiller to generate a second cycle without increasing the energy usage of the entire device.

Open energetic cycle: A second, open energetic cycle for the distiller is depicted in Figure 4.2.

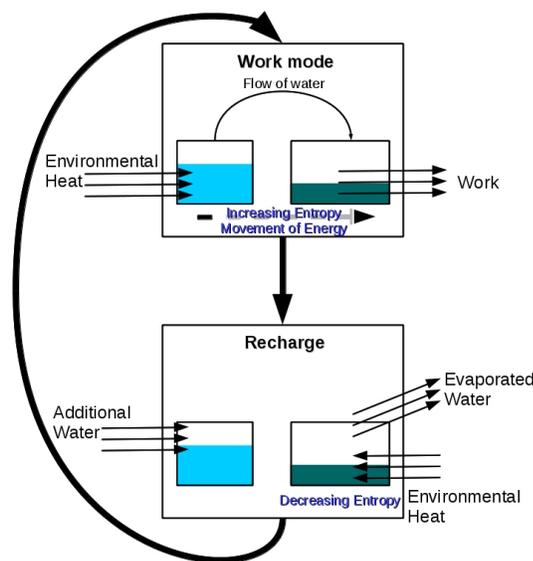


Figure 4.2: The open energetic cycle for the distiller.

In the open energetic cycle, the solution is dried through evaporation. As the draw solution is an aqueous solution of relatively low chemical activity, it can be dried by direct exposure to air with a temperature equal to or greater than room temperature. In this scenario, the energy required to achieve the recharge is the heat of the air, making it a direct energy source driving the distiller. While this does not recapture the water that enables the internal heat transport, it does eliminate the need for an additional energy source outside of that required to generate the initial wet vacuum and operate valves.

DISCUSSION

The generation of clean water from existing supplies of brackish or sea water, generally speaking, comes down to the availability of energy. In a world where clean energy was freely available in virtually any amount, it would be possible to generate as much clean water as needed for human uses and environmental maintenance and remediation. In a world increasingly facing difficult aspects of climate change including drought and flooding, both of which eliminate usable water resources, it is important to generate sources of clean water that are energetically clean, can take advantage of either already spent energy or a completely clean supply, and are technologically simple so as to engage all peoples in the use of the technology.

Enhancement

The entrocchemical distiller uses entropic changes and environmental heat to drive its distillation processes. As a result of this, it does not require generated power to function outside of the energy necessary to set up the system. Our interest is in accomplishing two goals:

1. Enhance distillation that is already going on without requiring new generated energetic input.
2. Make a distillation process available which does not require any generated power and can therefore be put into place without creating any carbon footprint.

This technology would seem to fit the bill on both counts.

Let us first assume the existence of a distillation technology that draws water from an appropriate draw solution, such as a CaCl_2 solution. It has been reported that adding salt to the solution doesn't significantly increase the energetic cost of distillation[1]. Therefore, the initial energetic cost is relatively unchanged as compared to distilling seawater in distilling this draw solution⁴. Now, taking the concentrated draw solution from the distiller enables the use of the entrocchemical distiller, increasing the overall yield by as much as 80% in the higher temperature range. Seawater or brackish water can be used to generate the thermal gradient and then can be cycled into the distiller, resulting in no brine generation and a significantly increased overall yield.

In many situations distillation facilities using high temperature output from power generators or on-sight heat generation might be impractical. However, creating structures that can acquire and hold solar energy so as to reach temperatures of 58°C is an achievable goal, even in relatively poor countries. In these locations, CaCl_2 or other solutions can be dried using airflow from a solar chimney or even by simply laying them out and allowing natural airflow to circulate air over them. Generating the wet vacuum conditions can be done by hand or using wind turbine-generated mechanical or electrical-to-mechanical energy. As a result, using this distiller design, which requires no specialized materials, filters, high pressure equipment, or other expensive parts or equipment, even developing communities would have the capacity to meet their clean water needs. In particular, island nations which may lack both clean water and energy resources can use this technology to meet their water needs using resources they have in abundance: ocean water and sunlight.

As we've indicated, energy is the great limiting factor in clean water generation. In order to estimate the amount of energy needed to run this distiller, we can calculate the amount of energy required to bring ocean water to the 58°C. We assume that we have a heat exchanger that transfers thermal energy between incoming and outgoing water streams and that the incoming stream is at an initial temperature of 25°C.

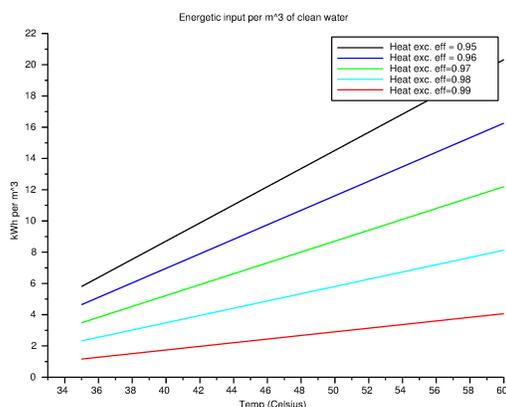


Figure 5.1: The energy required to heat incoming water to the high temperature defines the energetic input to the system and is highly affected by the heat exchanger efficiency.

In this configuration, energy input for heating the water is required, and this is illustrated in Figure 5.1. The amount of energy varies from just over 1 kWh/ m^3 to just over 20 kWh/ m^3 . In the best of these cases, the thermal energy could be supplied with an exposed surface absorbing thermal energy at an average rate of 600 W/ m^2 and two square meters of area. Increasing to 21 kWh would require at least 35 square meters. However, these are achievable goals even in the developing world, meaning a moderate facility of 35000 square meters could generate 10000 m^3 of clean water per ten hour day, enough to supply more than 260000 American households.

Enabling

One of the most important results of this study is the result that the NMK-based distiller functions and has a volumetric efficiency of as much as 60% . This is an extremely important result when viewed in the context of the open energetic cycle. The NMK solution appears to be a solution that can be spontaneously reduced in volume, and thereby increased in concentration, by simple evaporation at low temperature and relatively benign environmental conditions (low to high humidity, low to high temperatures). As a result, the recharge part of the energetic cycle can happen spontaneously in many environments that are human habitable.

The use of this technology is therefore absolutely accessible to virtually all people's worldwide. The solution can be dried by using conventional drying processes which utilize any amount of passively generated airflow (or none at all) over a device with a large surface area. The surface area can be increased by using absorptive materials such as cloth, paper, and many others. As the solution evaporates, it stores energetic potential which can be used to generate clean water.

The only technical requirement that must be overcome is the use of elevated temperatures with the distiller itself and the ability to generate and hold a mild vacuum. As we have noted in Section 5.1, the requisite heat can come from sunlight with a properly constructed structure and properly constructed heat exchangers can limit how much energy is needed to increase the temperature of incoming water streams, collecting heat from outgoing water streams. As a result, the overall system could be constructed virtually anywhere using indigenous materials with minimal of technical expertise or maintenance. Moreover the system can be modular and scalable, making it possible for entities to begin by building small systems, and then scale up with duplication and/or construction of scaled versions.

CONCLUSION

We have introduced a technology called an entrochemical distiller. This distiller uses an entrochemical process to generate an internal thermal gradient which is subsequently used to distill contained water. The device evaporates water at the warm side of the internal thermal gradient and condenses it at the cold side, recapturing most of the heat of vaporization. The device requires an internal concentration gradient between two water reservoirs to function. The system performance is characterized with two high concentration solutions at varied operating temperatures.

When enough water is transferred to the higher concentration reservoir, the contained liquid must be recharged. The recharge process can occur using a distiller in the closed configuration, representing a water distillation mechanism enhanced by the entrochemical distiller, or it can be recharged using an evaporative process in the open configuration, representing a method capable of using acquired environmental thermal energy to drive the system.

We demonstrated that our distiller can function at volumetric efficiencies of as much as 83.1% using draw solutions that can be recharged using environmental thermal energy and at temperatures that one could realistically obtain using passively heated solar thermal systems. As a result, the technology could be used by societies with extremely limited technical capabilities.

Future work will include improving the structure and design of solar chimney-based recharging technology, increasing the number of cells in the distiller enabling greater distillation rates, and expanding the number of different substances being used as draw solutions. We will also address methods of obtaining sea water in a way that eliminates the corrosive nature of the liquid being distilled. We will begin the work of integrating the distillation and recharge cycles. Finally, we will explore the possibility of merging this process with forward osmosis processes [8] as a way of generating electrical power.

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NONMENCLATURE

kWh per m^3	kilowatt hour per cubic meter
mL	milliliter
$^{\circ}\text{C}$	degrees Celsius
H_v	Heat of vaporization
$\frac{\text{W}}{\text{m}^2}$	watt per square meter
m^3	cubic meter

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