Ronald E. McNair Research Article

Developing Bio-Inspired Condensers to Facilitate Solar Desalination

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Abstract: World Resources Institute analysts indicate that more than 2.3 billion people globally live in environments with unsustainable access to fresh water resources. In response, scientists are developing novel methods of desalination—the removal of salt ions from saline water—to supplement current water resources. However, desalination requires a tremendous amount of energy to operate, which dramatically reduces its feasibility for poorer communities. Furthermore, desalination produces brine stream, which is a highly concentrated salt solutions that reduces water quality when discharged into the environment. This study aims to improve upon a novel desalination process while emphasizing zero-liquid-discharge (ZLD). Using a nature-inspired synthetic leaf comprised of a graphene oxide (GO) based material as a porous medium, saline water is evaporated using sunlight. Consequently, salt ions are separated from water molecules, leaving the resulting water vapor composed primarily of pure water. Measuring mass lost over time, the synthetic leaf demonstrates stable performance of evaporation with a 78% energy conversion efficiency at a rate of 2.0 L per m^2 per hour (LMH). The next phase of this research is to efficiently capture the water vapor by developing a bio-inspired condenser interface that utilizes a superhydrophobic-hydrophilic pattern. The efficiency of condensation depends on condensing surface temperature, water vapor convection rate, patterned vs. non-patterned surfaces, and ratio of hydrophobic to hydrophilic interlay. From these variables,

several testing skids will be designed for experimentation, evaluating the amount of water collected per condenser configuration. An optimized condenser, coupled with a robust high performing synthetic leaf will push the progress of solar desalination and aid victimized regions.

Introduction: There remains a prevalent need to satisfy the growing demands for fresh water. This challenge persists in the face of increased industrial activities, accelerating population growth [25], and sheer fresh water depletion [20], [23], causing significant depletions of potable water resources over the next two decades [12] - [18]. Some recent developments in water preservation focus on desalination as a viable method for potable water production. There have been numerous advancements in the field that aim to reduce energy consumption and improve cost efficiency on an industrial scale. For example, membrane distillation plants coupled with solar energy can operate at high temperatures in a non-continuous system, using as little as 1.2 kWh/m^3 to vacuum pump salt water—approaching with permeate flux ranging between 5 to 15 LMH via vacuum membrane distillation (VMD), making them comparable to industry-standard reverse osmosis systems [5], [6]. However, the process continues to draw fairly large amounts of energy due to fluid heating, around 100 kWh/m^3, and is dependent on the consistency of highly porous industrial membranes and a free heating source on site. If no free heating source is available, operation requires 75^{o}C, as opposed to 25^{o}C, which then becomes far too expensive energetically [3], [4].

Alternative methods like reverse osmosis membrane systems have been recorded to minimize the requirement of electrical energy to 2 kWh/m^3 for seawater desalination, at a water recovery rate of 50%. However, this process significantly decreases in efficiency as salinity increases—raising both the energy consumption and fouling/scaling potential, which drive up cost of operation. Operations such as the pretreatment and posttreatment of raw seawater take up additional energy outside of the reverse osmosis process, consistently reducing room for optimization in enhanced reverse osmotic systems [4]. More importantly, a significant setback to these processes is managing brine stream discharge.

Brine is the dense saline solution that exists as a byproduct of desalination. Numerous environmental issues such as beach erosion and the destabilization of osmotic pressure in seawater are a direct result of brine stream being discharge back into seawater feeds [2]. As brine poses an environmental threat, innovative methods are being developed to potentially reduce its impact, like crystallization into table salts or bioremediation [21], [24]. The former, however, requires more energy to purify the salt solutions into a crystalline form, and predicates the success and efficiency of the purification process on the profit of table salt, conjoining two markets, which runs the risk of reducing the feasibility of plant operation. The latter is seen in the development of microbial fuel cells, where anaerobic bacteria catalyze wastewater in a nitrification-denitrification process and channel ions across external wires in a chamber to produce a polarization of negative and positive charges. This transport of ions results in the separation of Na^+ and Cl^- ions in the desalination/ brine chamber via cation and anion exchange membranes, respectively [13], [19], [22]. However, bioremediation requires prudent oversight and must be tailored to sight-specific conditions, otherwise microbes may not function properly and their metabolic processes will fail to break down organic contaminants, resulting in toxic byproducts more mobile than the initial contamination [4]. Furthermore sight-specific solutions indicate that scaling the process will increase cost, as each plant will have unique characteristics that destabilize any standard financial foundation.

Due to the numerous barriers of current desalination processes, recent developments made to achieve zero-liquid discharge (ZLD), while reducing energy consumption, are highly desirable. Our current developments look towards enabling graphene-oxide (GO) nanomaterials to achieve high water separation performance, comparable to current commercial membranes, through nanosheet production that facilitate solar desalination. GO materials hold numerous characteristics that prove to be beneficial when developing membranes for ZLD. GO materials have innate propensities, such as adsorption of metal and organic dyes and photocatalytic degradation of organic molecules [12]. More importantly, when developed into nanosheets, GO show a robust chemical stability, strong hydrophilicity, and impressive antifouling properties. Numerous experiments show that GO nanosheets also have a high light-to-heat conversion efficiency, mesoscopic porosity, and efficient light absorption bandwidth up to 97% [7], [12], [13]. These characteristics suggest that GO nanosheets hold great potential to be a sustainable material for solar-powered desalination. As a result, our lab has developed a material, enabling the graphene-oxide nanosheets—cross-linked with triethylenetetramine (TETA) and 1,4 butanediol diglycidyl ether (BDGE)—for solar desalination. Several experiments indicate that when saltwater was evaporated through GO media, its properties enabled it to reject unwanted solutes via size discrimination and charge effects [7], [12]. This property achieves steam generation and salt crystallization simultaneously, successfully desalinating saltwater with ZLD. I will refer to our previous publication to explain the development and performance of the nature-inspired synthetic leaf [7]. However, the results of the leaf's evaporation properties show a high efficiency that has prompted the development of new technologies of biomimetic condensation interfaces that hold comparable, if not greater, efficiency in water condensation to facilitate the final stages of solar desalination.

As a result, research has been oriented around the Namibian Desert beetle, *Stenocara gracipiles*, which has adapted to its arid environment by using hydrophilic protrusions on its elytra to capture fog-laden wind. The protrusions are patterned throughout the elytra, ranging between 0.5-1.5 mm apart from one another [11]. The diameter of these protrusions is measured to be approximately 0.5 mm and rest on top of a hydrophobic background [1], [11], [16]. The natural equivalence of hydrophobicity for the beetle indicates waxy coating that covers the majority of its forewings, while the hydrophilic bumps are nonwaxy, allowing water to coalesce once it comes in contact [3], [10], [11], [16]. The Namibian Desert beetle serves as the inspiration for biomimetic condensation interfaces that could function to be a suitable tool to enhance solar desalination while reducing energy consumption.

In previous studies regarding the development of such interfaces, laboratories have characterized that optimal collection efficiency can be approached on surfaces with high contrast wetting patterns that implement a dotting formation, mimicking the beetle's elytra [16], [27]. However other factors influence water collection efficiency and need to be considered, such as: (1) The energy barrier for water nucleation on a surface. The barrier decreases in magnitude if the surface has a propensity to attract water, indicating hydrophilic surfaces require less energy to collect water better than hydrophobic. While that may be obvious, it is essential information when developing biphilic condensation interfaces that require a ratio of hydrophilic and hydrophobic interlay, as too much of either material can dramatically reduce collection efficiency [10]. (2) Temperature of the interface must consistently remain lower than ambient temperature to ensure droplet nucleation. (3) And the presence of surface patterns/defects improve nucleation, in some cases by nearly 60% [1], [16], [26]. Additionally, surface inclination and water contact angles may also play an important role. The simple hydrophilic or hydrophobic substrate perform differently depending on how the surface comes in contact with fog or dew, where hydrophilic substrates perform well at higher angles of inclination approaching 90º due to the assistance of gravity and increased momentum of droplets. Whereas hydrophobic substrates perform better at lower inclinations respectively, near or equal to 90º to the horizontal, due to the reduction of contact angle hysteresis [1], [8] - [11], [16]. Ergo, variables such as contrast wettability, condensing surface temperature, patterning vs. non-patterning, and surface inclination are major factors that affect the water collection rate, and need to be considered when optimizing our condensation interface.

The aforementioned variables in previous research will be accounted for and tested in the following experimentation as a means to exploit new iterations of biomimetic condensation interfaces. It is important to denote that previous research focus on the condensation of fog and dew—which have a droplet diameter up to 0.040mm—as a source of drinking water [10]. However, this research aims to unearth the efficiency of condensation interfaces in the presence of water vapor developed from synthetic leaves, which have a dimensional range of 0.001mm to 0.014mm [3].

Materials & Methodology:

1. ***Synthesizing simplified Graphene-Oxide and Reduced Graphene-Oxide Leaves***

The synthesis of GO and rGO synthetic leaves is two-fold; (1) GO Nanosheet Preparation and (2) GO Leaf Fabrication. GO nanosheet preparation follows the Hummer's method and produces freezedried particulate that is sonicated and purified in deionized water and cross-linked with TETA and BDGE as mentioned earlier. This cross-linking creates the durable leaf, which we then put in a tree like configuration to optimize its water evaporation rate. The complete synthesis can be found in our previous publication [7].

2. ***Biomimetic Condensation Interface Development***

   a. ***Water Vapor Production***

In order to a generate consistent amount of water vapor at various rates, we are designing a nebulizer that will function as the synthetic leaf for the duration of the experiment. Items needed for the nebulizer are an ultrasonic mist maker (Lemonbest 24V 12 LED Ultrasonic Atomizer), a small fan (Thermaltake Mobilefan II) to circulate the water vapor, pair of 9V batteries with On/Off switch holders (Gino) for the fan, 2” flexible tubing (CENTRAL VACUUM FLEX TUBE; 36” long) to transport the water vapor to the condensation interface, and a clear plastic gallon jar container to house all materials (Kirkland 55 oz.).

   b. ***Water Transport and Interface Contact***

Once the water vapor is generated within the nebulizer, the flexible tubing extending from the inside of the nebulizer will connect with a 24” acrylic tube (Source One LLC) that leads to the condensation interface. The interface will be developed using copper mesh with ¼” (6.4mm) dimensions (Amaco Wireform Mesh) that will function as the relatively hydrophilic substrate. Painter’s tape (Scotch Blue) and adhesive double-sided dot tape (eQualle Acrylic Glue Kit) will be used to developed specific patterns that will test water collection efficiency on 4 different substrates (i.e., dotted protrusions, diagonal, vertical, and horizontal strips). As the painter’s tape partitions the hydrophilic surface, we will use hydrophobic spray (Vans, ALDO, NeverWet) to develop high contrast wetting patterns on the uncovered portions of the interface. Conservation of energy dictates that the same thermal energy inputted to evaporate the water into vapor will be redistributed on the interface once the vapor begins to condense, causing the interface to heat up over time. To maintain a relatively constant surface temperature, we will place a Thermoelectric Peltier Cooler (AliExpress DIY Kit) on the underside of the substrate which will allow it to dissipate heat generated during condensation. In order to automate the cooling process, a thermocouple (tMP36, TO-92 Adafruit) was placed on the TEC and connected to a serial monitor using a single board microcontroller Arduino (Arduino UNO). The thermocouple and TEC established a communication via the Arduino board and automates the dissipation process whenever the TEC reaches a temperature outside of its known range, which will vary depending the on the energy inputted in the vapor production phase. Lastly, the nebulizer and the condensation interface will be housed in a closed chamber, as a way to control humidity and reduce ambient effects on the water collection rate.

c. Arduino Setup

Arduino UNO is the specific model of the open-source electronics prototyping platform that functions as a miniature computer. It interacts with other devices using lights, sensors, and motors. Materials needed to develop the TEC – thermocouple communication are a breadboard (Adafruit) to establish closed circuits, jumper wires (ELEGOO) to connect the Arduino UNO to the TEC and thermocouple via the breadboard, thermocouple, TEC, tape to hold down the thermocouple onto the TEC, and a continuous 12V power source. We developed our power supply from wiring two 9V batteries in series for the first several tests.

3. Measurements

The water vapor production output of the nebulizer can be measured using gravimetric analysis—measuring the weight of the nebulizer before and after vapor production, with known variables like container volume and volume of water sonicated. The water collection rate will be measured by the change in mass on a load cell over time per unit area of the interface. Each experiment will run 60 minutes and collect data on change in weight every minute. Certain parameters of the environmental chamber set up is inspired by Gerasopoulos et. al, and will maintain the chamber to 37^{o}C with a relative humidity of 98% to diminish variations in ambient conditions [11]. The surface interface will be angled using a goniometer and two ring holders clamped on the perimeter of the interface. The goniometer will vary the surface angle between 0^{o} – 90^{o}. Additionally, a water contact goniometer will be used to measure the advancing and receding water contact angles on each surface respectively as a means of minimizing contact angle hysteresis.

Hypothesis: Based off of previous data and experimental parameters, the development of a biphilic condensation interface with dotted hexagonal patterns mounted ~45^{o} angle should optimize water condensation rates. The interlay of hydrophilic and hydrophobic portions of the interface allow it to have complementary qualities that can aid the coalescence of droplets on hydrophilic protrusions, while the relatively hydrophobic background will aid in the roll-off of large droplets. The 45^{o} mount is to create uniform pattern of water droplets across the array of hydrophilic bumps. The hexagonal design is simply in correspondence with the characterization of the Namibian beetle, however it has not been characterized whether a hexagonal dotted pattern outperforms a random dotted pattern. The creation of dotted patterned surfaces with current materials may not produce a dramatic increase in efficiency as previous data may suggest, due to the dimensions of the circular protrusions not exactly matching the dimensions of the hydrophilic bumps of the Namibian Desert beetle. For instance, the diameter of the beetle's bumps is understood to be most efficient at 0.5 mm, however the dotted adhesive tape used in the experiment is initially 35.56mm, so modifications need to be made which introduces error into the experiment. Other forms of error may include the height of the protrusions, the impact of ambient conditions such as room temperature fluctuations, and the response time for the TEC to dissipate heat from the interface, causing a decrease in condensation due to the increase in surface temperature compared to ambient temperature. These deviations will be accounted for during experimental procedure.

Conclusion: There are numerous advancements taking place in the field of desalination, however most nuances still require either an immense amount of energy or produce dense saline solutions that deplete the quality of current saltwater feeds. Recent developments in zero-liquid discharge have led to the novel generation of GO synthetic leaves that use solar energy to efficiently desalinate saltwater at far greater rates than current commercial methods. The development of synthetic leaves and steam generators have called for a push in new condensation interfaces that can capture water vapor produced at great rates via synthetic leaf. These condensation interfaces will contain biphilic compositions that allow water to coalesce on hydrophilic protrusions and roll-off on a hydrophobic background. The dimensions of hydrophilic protrusions should be no more than 0.5mm and the distance between these bumps should range between 0.5 – 1.5mm. This research aims to corroborate these findings in the presence of smaller droplets from water vapor, as opposed to dew or fog. Our current experimental procedure has recently established the digital communication between the thermocouple and the TEC and is transitioning into the development of the condensation interface.

This work derives its significance from the billions of individuals that currently are living without consistent access to fresh water. The development of these biomimetic condensation interfaces will close the loop on the growing field of solar desalination by effectively reducing energy consumption and increasing feasibility of global implementation. More so, this research of GO leaf evaporation and biomimetic condensation can potentially unlock seawater as a viable water resource for *all* countries globally.

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