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Enhancement of Atmospheric Water Harvesting via Salt-Infused Sponges and Peltier Devices †

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Abstract: Despite the demand for clean water, it is commonly deficient. In the past two decades, there has been renewed interest in the development of clean water generation processes from atmospheric moisture. Atmospheric water generation is a 2-stage process; in the first stage, the moisture is accumulated in an absorber material, and in the second stage, the absorbed moisture is recovered to a vessel by thermal and/or mechanical processes. One of the keys to achieving high efficiency in such processes is the moisture-absorbing agent, which works passively without electricity. Several materials are currently under research, such as metal-organic frameworks (MOF) and hygroscopic salts. However, most approaches would likely be challenging to scale up from technical and economic perspectives. This work aims to develop a commonly accessible, cost-effective, environmentally friendly, and highly effective moisture absorber. Calcium chloride ($CaCl_2$) was chosen as the main salt of interest due to its deliquescence; however, it is known to suffer from agglomeration upon repeated absorption-desorption trials which decreases efficacy. To overcome this problem, a simple infusion of the salt into the sponges significantly reduced the agglomeration problem of the salt while also improving its absorption rate and maximum water uptake by ~30% at 27 °C and 80% relative humidity (RH) compared to a sample without the cellulose sponge. To elucidate the science behind this synergistic interaction, time-dependent water uptake measurements at controlled conditions were carried out using a microbalance in an environmental chamber. Then the data was analyzed using a double exponential equation. A physical model of the moisture absorption mechanism in the salt/sponge system was proposed. Finally, a complete atmospheric water generation device prototype was demonstrated by incorporating the salt/sponge absorber into a custom-designed Peltier-based distillation chamber.

Keywords: moisture absorber; clean water generation; peltier distiller

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1. Introduction

It is accepted fact that water is the most important substance to living organisms. Nonetheless, some areas lack access to water which is concerning given how essential it is. Areas that lack natural clear water sources and/or access to water distribution have very few options are available to obtain clean water. One of these may be harvesting rainwater, though it comes with risks of chemical and microbiological contaminations [1]. Furthermore, it is not reliable to expect a consistent event of rain throughout the year.

Thus, more recently, efforts to generate clean water from the atmospheric moisture are gaining some interests [2–7].

Generally, generating clean water from atmospheric moisture consists of a two-stage process. The first stage pertains to the harvesting of atmospheric moistures into a hygroscopic absorbing media [1]. In the second stage, the absorbed moisture is separated from the hygroscopic media into a recovery vessel as clean water. This is achieved using well-established methods such as reverse osmosis [1] or distillation processes [1]. After moisture recovery, the absorbing media can reabsorb moisture and the cycle continues. It should be noted that the efficiency of the atmospheric clean water generation process depends on advancement in both the moisture recovery methods and the moisture-absorbing materials.

Several studies in the past have examined the moisture absorption capabilities of various media, including those that are complex and difficult to produce commercially. Some of the most distinguished media are those such as $CaCl_2$ in an alginate-derived matrix (Alg-$CaCl_2$) [2], multiple versions of metal-organic-framework (MOF) materials including namely, MIL-101(Cr) [3], Cr-soc-MOF-1 [4], Co2Cl2 (BTDD [5], activated carbon such as AC07 [6], and MOF-801 [7] as shown in Table 1.

Table 1. Comparative analysis of water uptake amongst various media containing $CaCl_2$.

Name	Medium	Water Uptake (%)	Conditions (Temperature, Dewpoint [°C], Water Vapor Pressure [mbar], RH [%])	Reference
Alg-$CaCl_2$	Alginate based	288	28, 24.1, 30, 79%	[2]
AC07	Activated Carbon/SiO_2	39	27, 7.9, 10.7, 30%	[6]
MIL-101 (Cr)	MOF	88	30, 10.6, 12.8, 30%	[3]
Cr-soc-MOF-1	MOF	200	25, 19.1, 22.2, 70%	[4]
MOF-801	MOF	30	25, 6,2, 9.5, 30%	[7]
Co_2Cl_2 (BTDD)	MOF	90	25, 6,2, 9.5, 30%	[5]

The most prominent options are Cr-soc-MOF-1, which can absorb 2.0 g of water per gram of salt or 200% of its mass at 25 °C and 22.2 mbar of water vapor pressure, and Alg-$CaCl_2$ which can absorb 2.88 g of water per gram of salt or 288% of its mass at 28 °C, 79% RH, and 30.0 mbar of water vapor pressure [2]. Despite these excellent innovations, scaling up moisture harvester technologies based on the materials may be challenging due to the intricate crystal making requirements—in the case of the MOFs—or the need to extract alginates from their origin, for example, the brown algae.

This work demonstrates the development of a simple and effective moisture harvester alternative material that is scalable and high performing. The moisture harvester is based on a common hygroscopic salt, $CaCl_2$, which is praised as one of the most hygroscopic salts readily available. $CaCl_2$ is also deliquescent, meaning that it absorbs moisture in the air until it dissolves to form a brine. Deliquescence is a property found to be maximized at low temperatures and high humidity [8] as it occurs when the vapor pressure of this brine solution is lower than the partial pressure of the vapor pressure of water in the air [9]. Although calcium chloride itself has excellent water absorbing capabilities, it must be complemented by another material due to its penchant to agglomerate. Agglomeration occurs when fine particles are chemically and physically bonded, "clumping up together in a floc" [10]. As shown in Figure 1, agglomeration occurs in calcium chloride when it liquifies and is dried again to be reused.

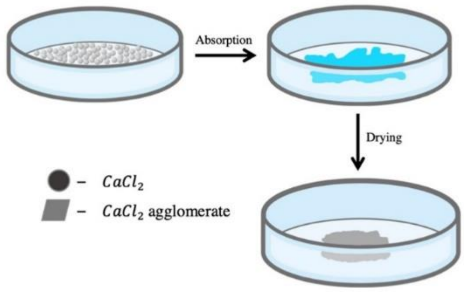

Figure 1. Illustration of agglomeration processes of calcium chloride salts upon moisture absorption and drying. The clumping reduces the amount of surface area in direct contact with the moist environment.

To solve this problem, we investigate the potential of utilizing a simple sponge-salt system to overcome the agglomeration problem of deliquescent salts. Four commercially available types of sponges were first screened for their best performance. Then, a more thorough investigation is carried out for the best sponge identified. Moisture absorbance measurement is carried out over time in a constant temperature and humidity. The moisture absorption time dependence was analyzed using a basic exponential model where the time constant and other absorption parameters were extracted and analyzed. The analysis reveals improvements in the sponge-salt system's water absorption rate and capacity than the salt system alone. A model is then proposed based on two mechanisms that highlight the existence of two distinct absorption mechanisms. Finally, a proof-of-concept water recovery Peltier-based system is proposed.

2. Methods

2.1. Sample Preparation

Each sponge of same size was pre-dried and was injected with 0.2 mL of 5 M $CaCl_2$ solution. It was ensured that the solution was evenly distributed. The sponge was then dried in the oven at 60 °C for 12 h on a petri dish with its lid. The mass was measured to quantify the salt content in the sponge. The sponge-salt samples were then ready for water absorption measurement. The salt control was created by evenly spreading out an equal mass of salt as the salt content in the sponge on a petri dish.

2.2. Moisture Absorption Time Dependence Measurement

The materials were placed on a microbalance inside a temperature and humidity regulated chamber. Weight changes of the samples were monitored and logged over time using a custom program written in in LabVIEW. Measurements were carried out at a constant temperature of 27 °C and humidity level of 80% RH. After the absorption measurement, the sponge was put in the oven for 12 h at 60 °C to run the next trial.

3. Results and Discussion

3.1. Preliminary Experiment

Four types of sponges were tested to decipher the most effective sponge: cellulose, soundproof, magic, and Dacron (Figure 2a). The results were normalized to the salt's mass in the respective sponges. Hence, it is evident that the cellulose sponge was the most effective as seen in the water uptake vs time graphs in Figure 2b. Water uptake percentage was defined by $\frac{mass_{moisture\ absorbed}}{mass_{salt}} \times 100\%$. Control measurements of each of the sponges without salts does not show any water absorption effects. Thus in the next sections we focuses our investigation to the salt-cellulose sponge systems only.

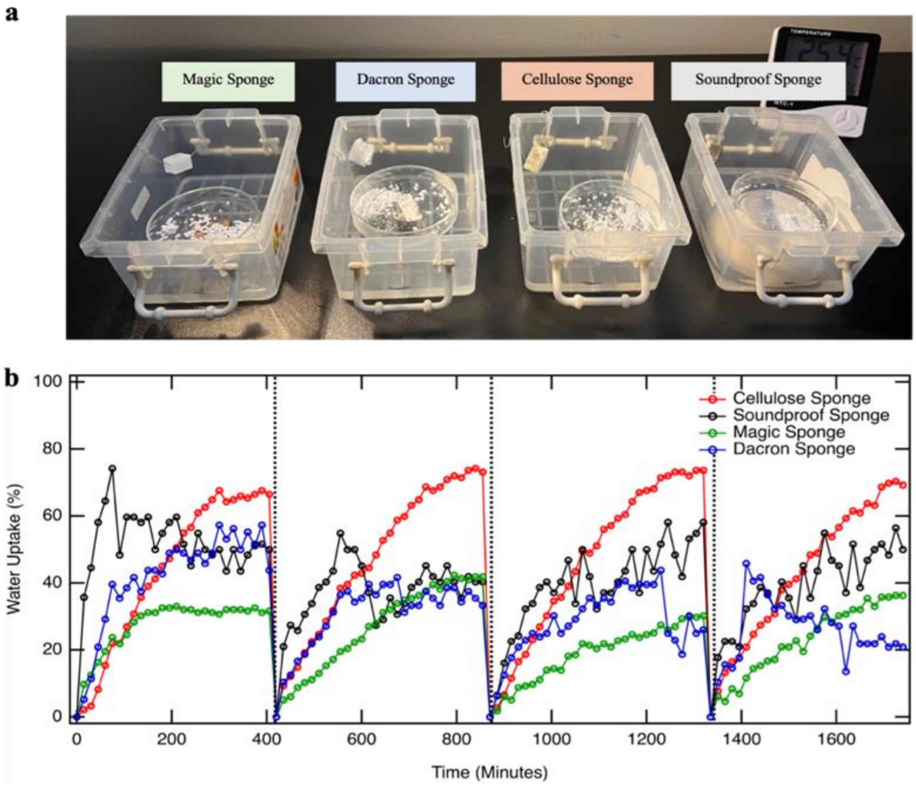

Figure 2. (**a**) Sponge types tested. Each container has a respective sponge and control; change in mass was measured every 15 min for 6–7 h. (**b**) Sponge type curves. Graph shows water uptake by various commercial sponges. They were soaked in 5M solutions, dried, and left to absorb. The vertical dotted lines indicate a new trial. The weight changes during the drying phase was not tracked except for the beginning and final weight.

3.2. Salt-Cellulose Sponge Water Uptake Time Dependent Measurements

The efficacy of the cellulose sponge was examined by testing its maximum absorption capacity by exposing it to a controlled atmosphere until the salts stopped absorbing moisture as can be seen in Figure 3. There are several key observations. First, we found that the water uptake dynamics fit very well to a double exponential model (Equation (1)), as listed below

$$W(t) = W_{saturated} - A_1 e^{\frac{-t}{\tau_1}} - A_2 e^{\frac{-t}{\tau_2}}, \quad (1)$$

where $W(t)$ is the water uptake percentage at a given time, $W_{saturated}$ is the maximum water uptake percentage, A_1, A_2, τ_1, and τ_2 are fitting constants. We confirm that a single exponential model cannot explain such behavior. This suggests that there are two types of water uptake mechanisms in our system. Secondly, it is evident that the sponge salt sample exhibit faster water uptake rate. Finally, the sponge salt sample was found to exhibit a higher maximum water uptake, $W_{saturated}$, of ~305% while for the control salt sample it was found to be ~272%. The salt sponge sample performed better than most of the previously reported moisture absorbers in the literature (Table 1).

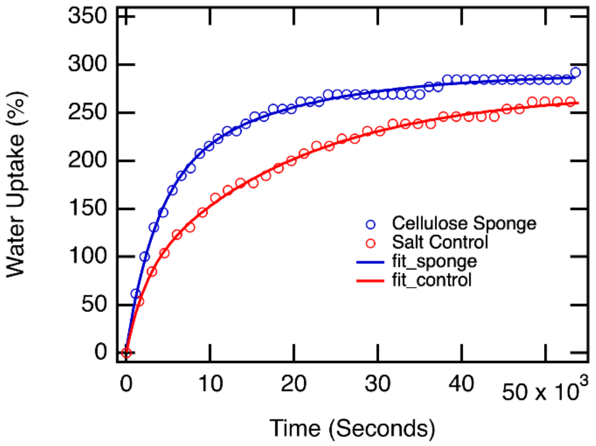

Figure 3. Time-lapsed water uptake of cellulose sponge. Solid line represents the curve fit using the double exponential equation (Equation (1)).

3.3. Proposed Model

Based on the enhancement observed from the water uptake dynamics, we propose a physical model as illustrated in Figure 4. In this model, salts are spread around the pores of the sponge. When the salts absorbed moisture, the absorption is homogenous throughout the sponges. This in effect causes an even salt precipitate distribution upon drying. As a result, the optimal amount of surface area of the salt species is maintained, for example, it does not suffer agglomeration problem. The optimal surface area would cause an improved water absorption rate. The infusion of the salts into the cellulose sponge results in both increase in maximum water uptake and absorption rate. More analysis is necessary to explain the improved maximum water uptake and the two absorption mechanisms that were observed in our system. Nevertheless, it is clear that the simple infusion of salts into the cellulose sponge provided significant improvements that are valuable in the context of atmospheric moisture clean water generation.

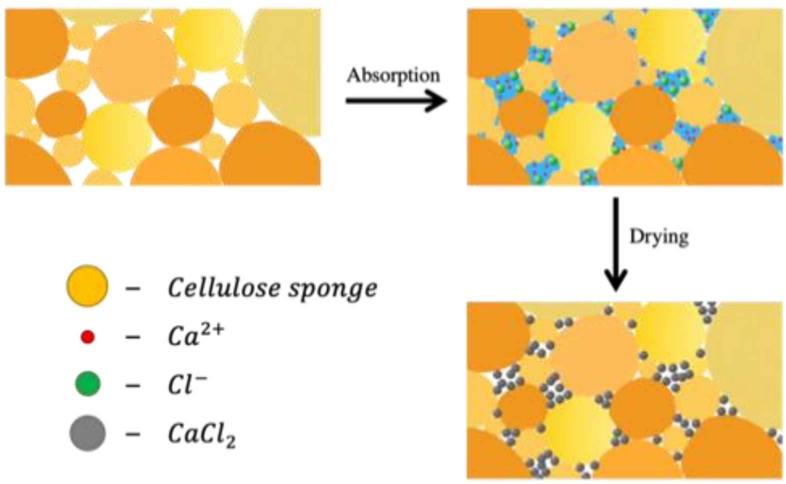

Figure 4. Proposed physical model of the salt-cellulose sponge system. Cellulose sponge with minimal agglomeration.

3.4. Peltier Device Prototype

To recover the absorbed moisture as clean water, a peltier-based distillation unit was prototyped (Figure 5). The unit was equipped with three water recovery channels to maximize the transfer of water droplet from the evaporation to the condensation chambers.

The primary channel was set directly under the acute end of the roof due where most of the vapor was accumulating. The secondary channel directly transfers moist air to collection chamber using a small DC motor pump. Finally, a tertiary channel is setup across from the acute end of the slanted roof to capture the flow of the larger water droplets accumulating on the top wall. The design also takes into account the temperature gradient generated by the peltier module which naturally lowers the temperature of the collection chamber.

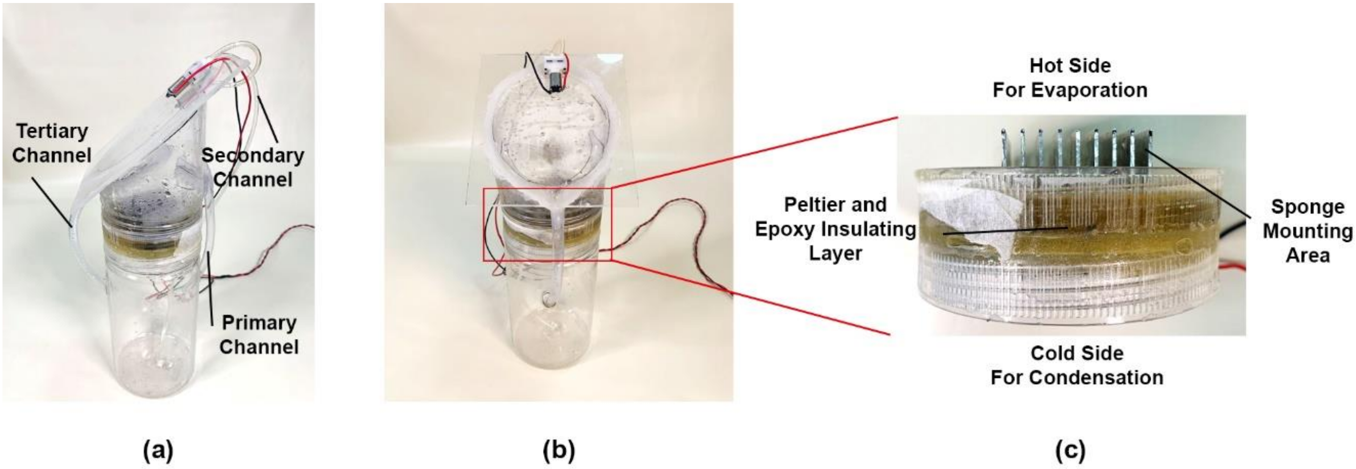

Figure 5. Prototype of the peltier-based clean water generator. (**a**) Side-view showing the three water channels to transfer water from the top evaporation to bottom condensation/collection chambers. (**b**) front-view. (**c**) View of the peltier module.

The device uses a single piece of peltier module (9 V, 2 A) in a small chamber with a diameter of 8 cm and generates ~5 mL of clean water/hour from atmospheric moisture. Although more optimization is necessary, we note that this system does not waste any sacrificial clean water as in most reverse osmosis or water distillation systems. More optimization is also possible including the incorporation of solar powered energy sources, development of a multi-module systems and better material choice to encourage formation and flow of water droplets on the walls of the evaporation chamber.

4. Conclusions

We found that by infusing calcium chloride into a cellulose sponge, faster moisture absorption and an increase in the maximum water uptake capacity (at 27 °C and 80% RH) up to ~305% are achieved compared to that without the sponge at ~272%. The sponge inhibits common problems with calcium chloride such as agglomeration and its deliquescence. The approach is simple, and relatively more cost effective compared to other moisture absorber materials. Cellulose sponge as a medium is simple, cheap, and environmentally friendly, energy efficient, and effective when absorbing moisture as shown by the salt absorbing moisture up to ~305%. A proof-of-concept device was also demonstrated utilizing a 3-channel water collection pathways using a peltier device for generating the clean water from atmospheric moisture.

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Conflicts of Interest: The authors declare no conflicts of interest.

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