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

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1 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.

2 Ambient Temperature Collection

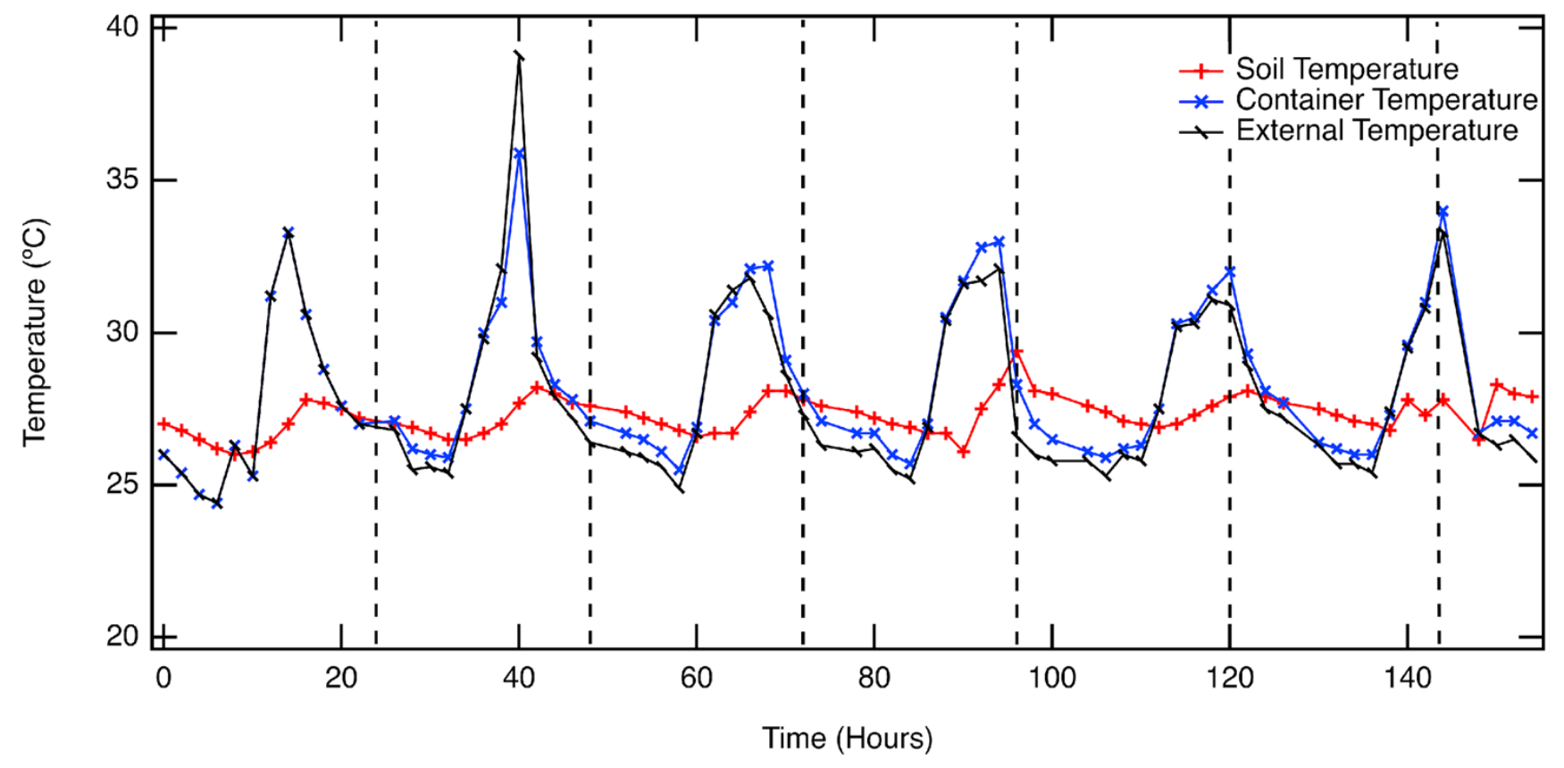


Figure 1 – Temperature inside the soil, inside the container, and outside in a span of 6 days (figure 4). The sharp falls indicate a new day.

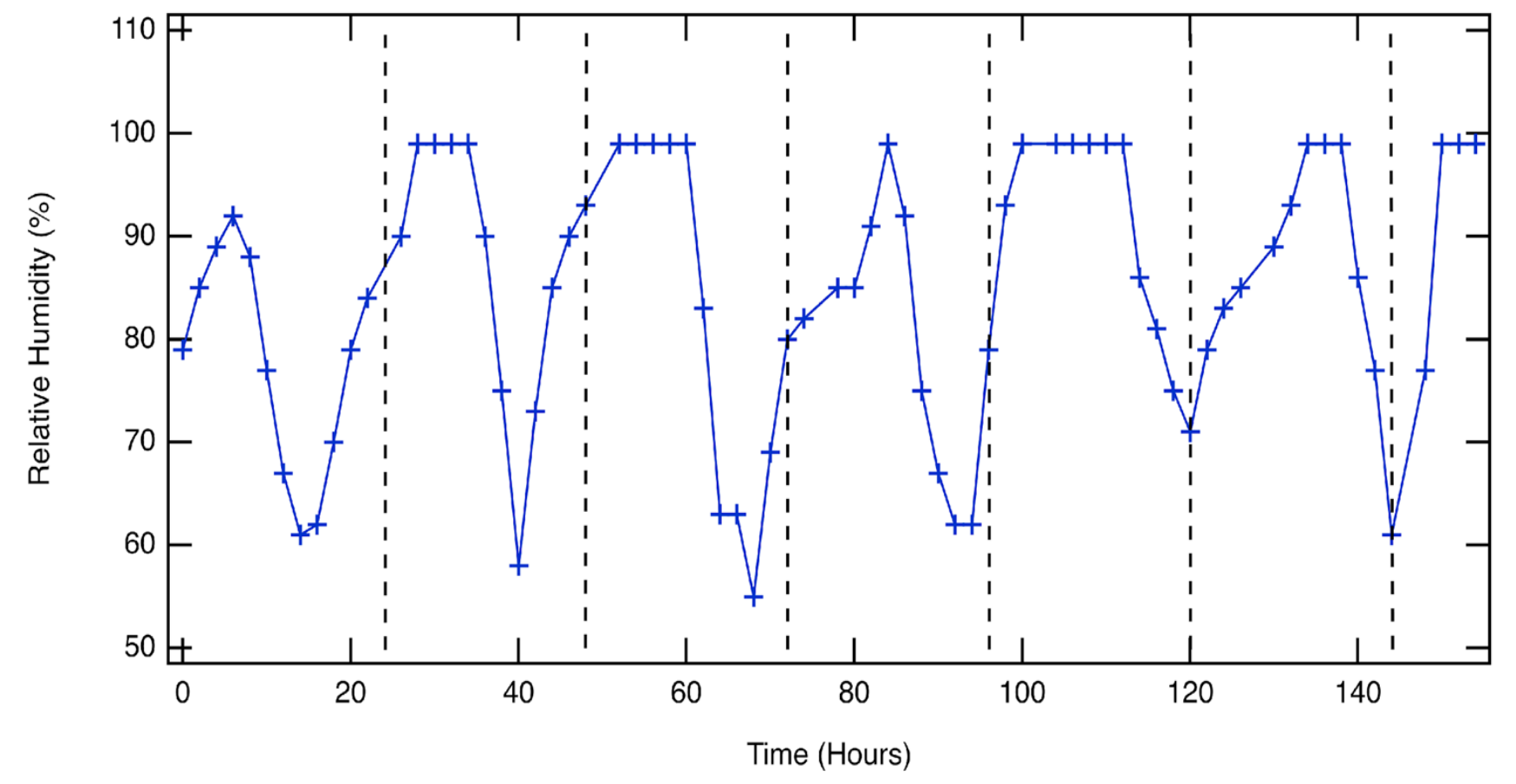


Figure 1 – Relativie humidity inside the container in a span of 6 days (figure 4). The sharp falls indicate a new day.

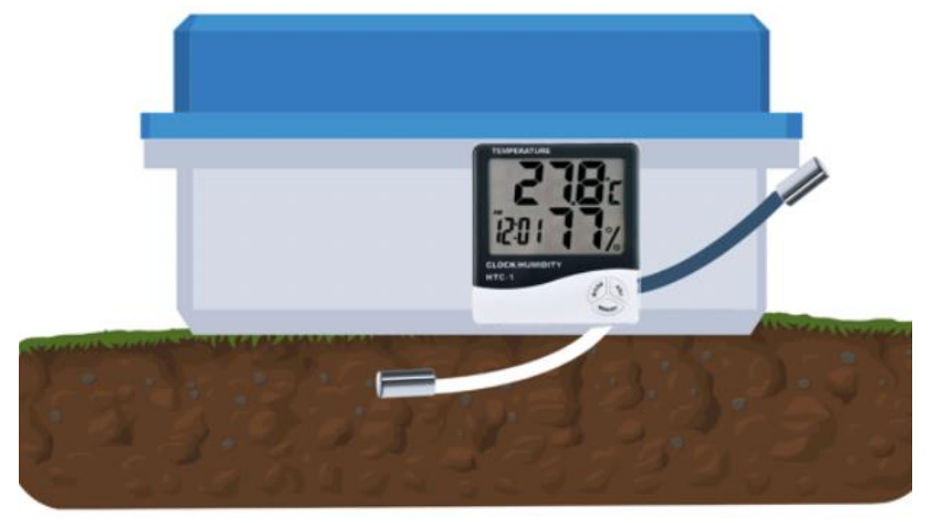


Figure 2–Temperature Apparatus

3 Sponge Screening

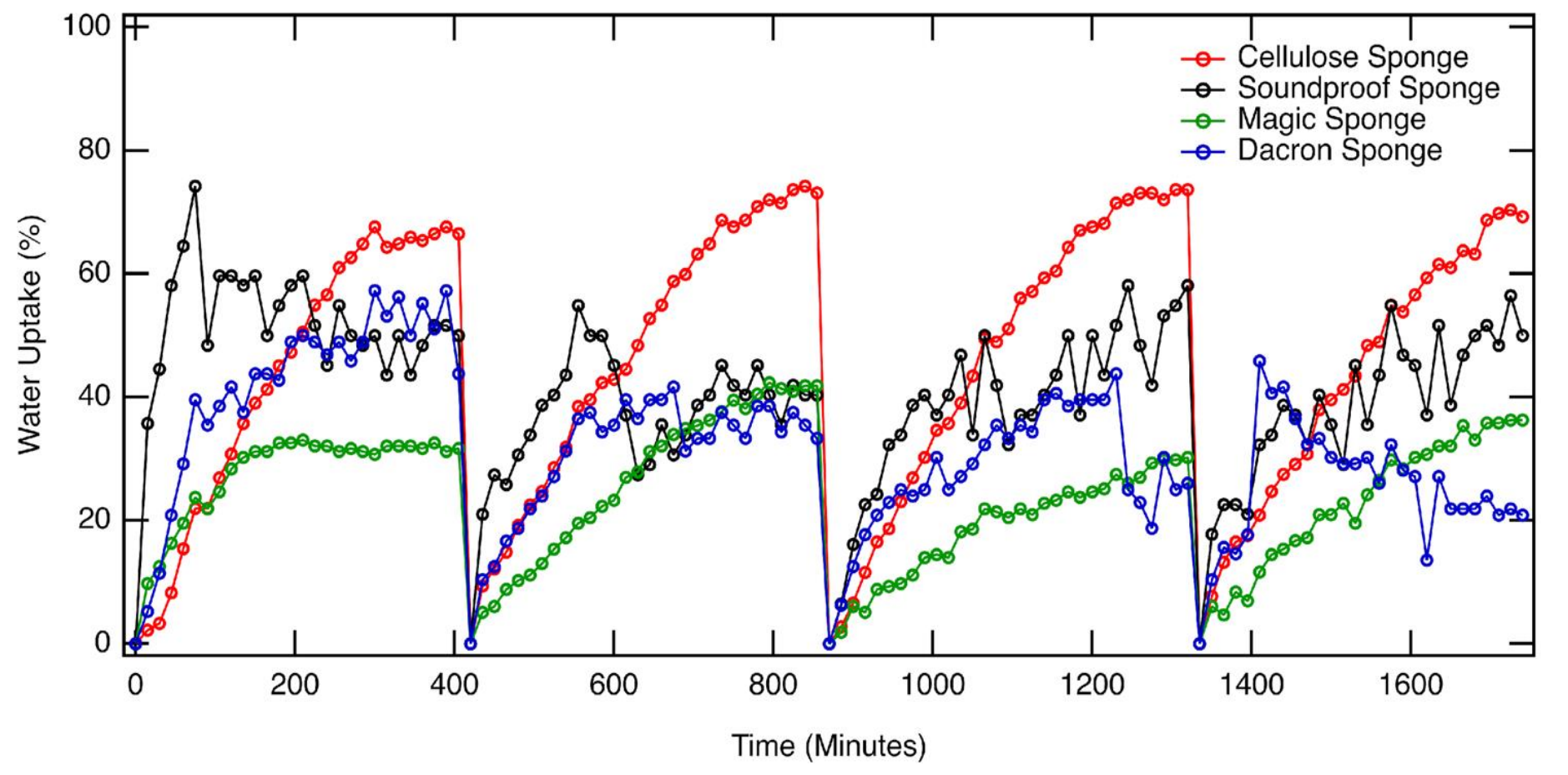


Figure 3 – Absorption capabilities of 4 commercially available sponges. Cellulose sponge was shown to be the most effective (figure 5-6). The sharp falls indicate a new cycle.

Figure 4–Sponges Tested

Figure 5–Collecting Data

4 Methodology

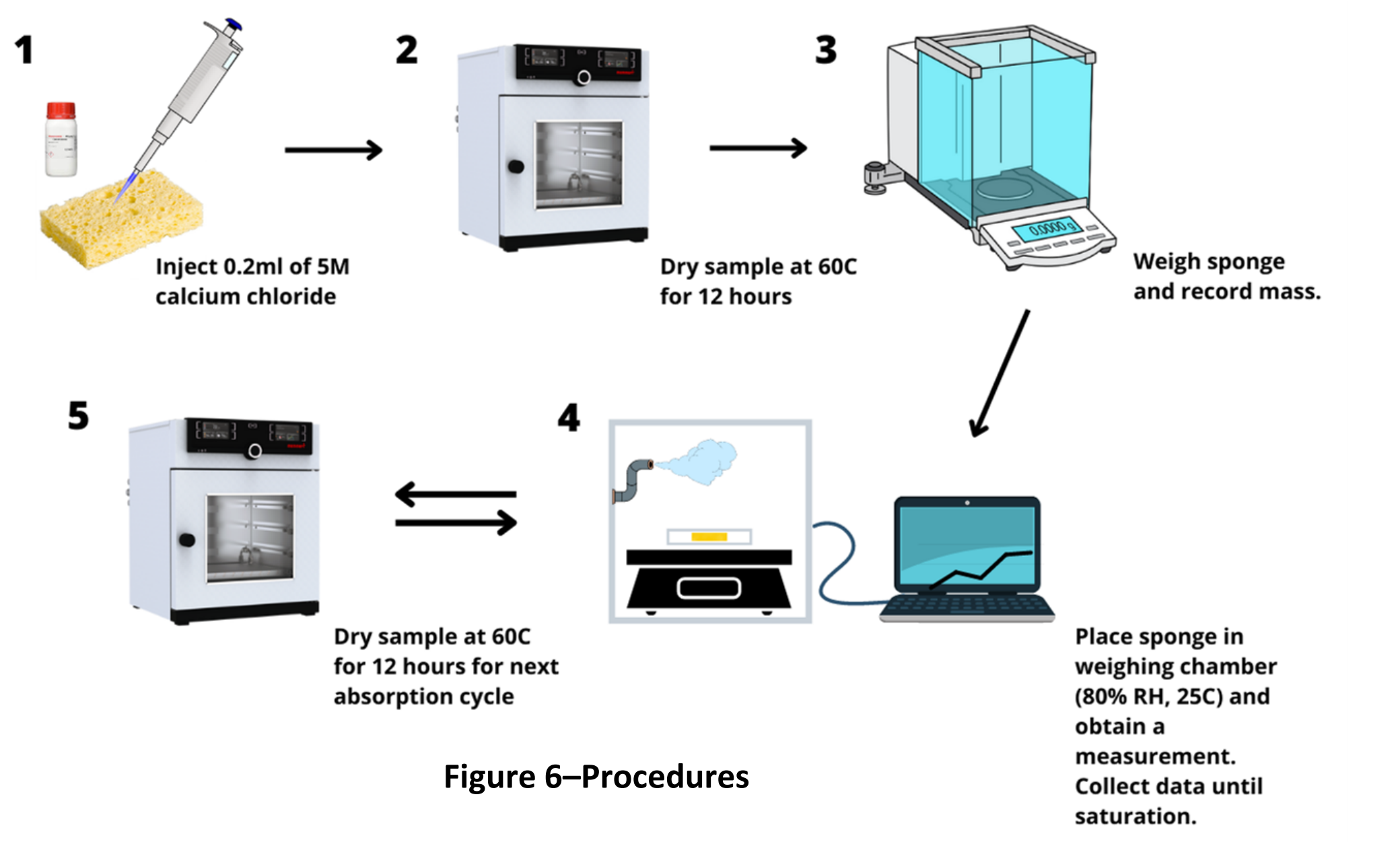


Figure 6–Procedures

Materials

1. Anhydrous $CaCl_2$
2. Cellulose Sponge
3. Distilled Water
4. Automatic Weighing Chamber (fig. 7).

*5M $CaCl_{2\,(aq)}$ was made prior to the method.

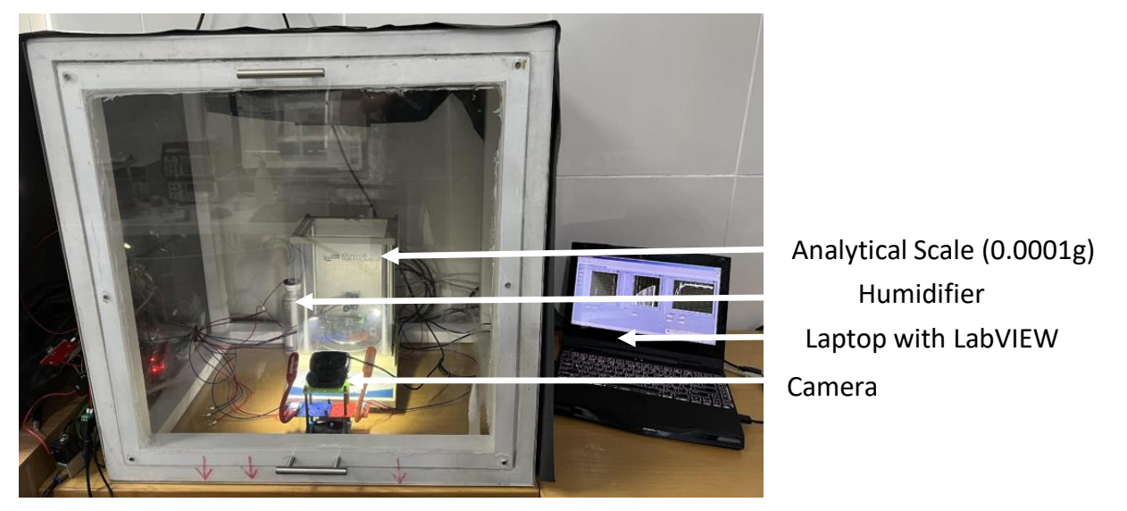
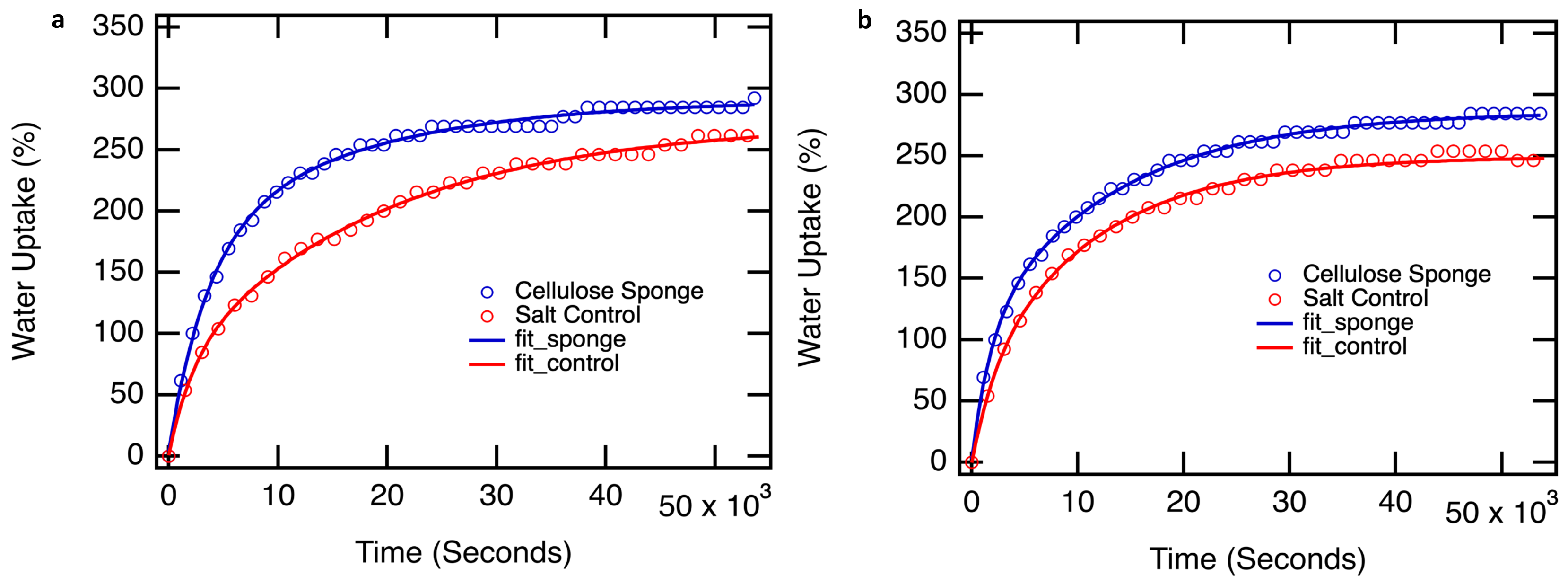
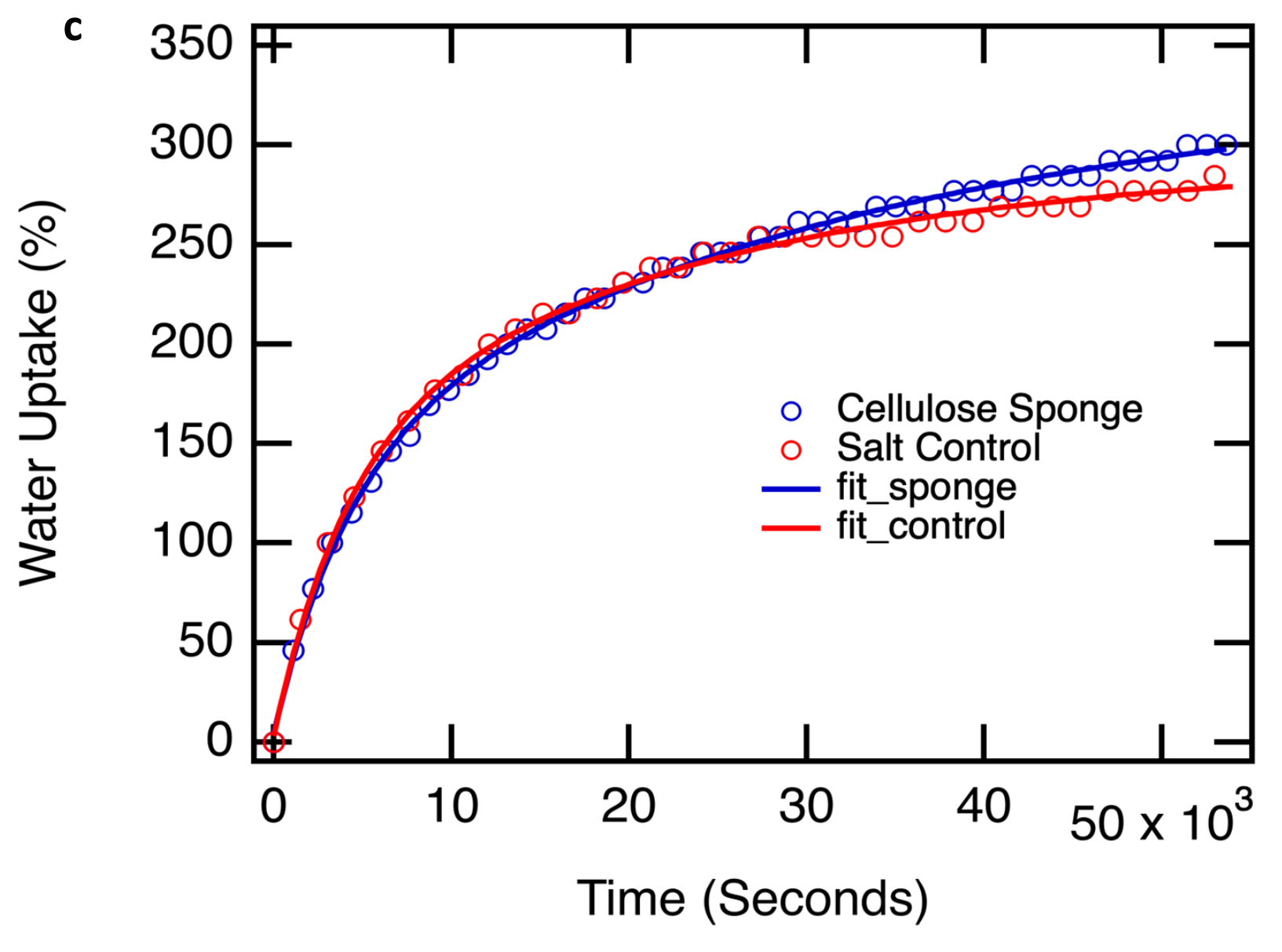


Figure 7–Weighing Chamber

5 Results

Figure 8 – Time-lapsed Water Uptake of Both Samples. (a), (b), and (c) represent the first, second, and third trial of moisture absorption respectively. Solid line represents the curve fit using a double exponential equation (equation 1).





Parameter	Trial 1	Trial 2	Trial 3
$W_{saturated}$	272.62	249.43	294.68
A_1	197.33	193.09	136.81
τ_1	19420.12	10839.29	24903.50
A_2	73.109	51.831	140.81
τ_2	2573.54	2233.14	5142.97

Parameter	Trial 1	Trial 2	Trial 3
$W_{saturated}$	290.96	286.45	336.98
A_1	116.69	175.11	188.45
τ_1	16232.45	13557.85	34066.91
A_2	161.13	95.544	134.77
τ_2	3872.82	2276.45	4969.19

Figure 9 – Two-stage Absorption Behavior Curve Fitting Constants. (a) Salt Control. (b) Salt/Sponge

Equation 1–Double exponential equation. Where $W(t)$ is the water uptake percentage at a given time, $W_{saturated}$ is the maximum water uptake percentage (asymptote), A_1, A_2, τ_1, and τ_2 are fitting constants to be interpreted in later sections.

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

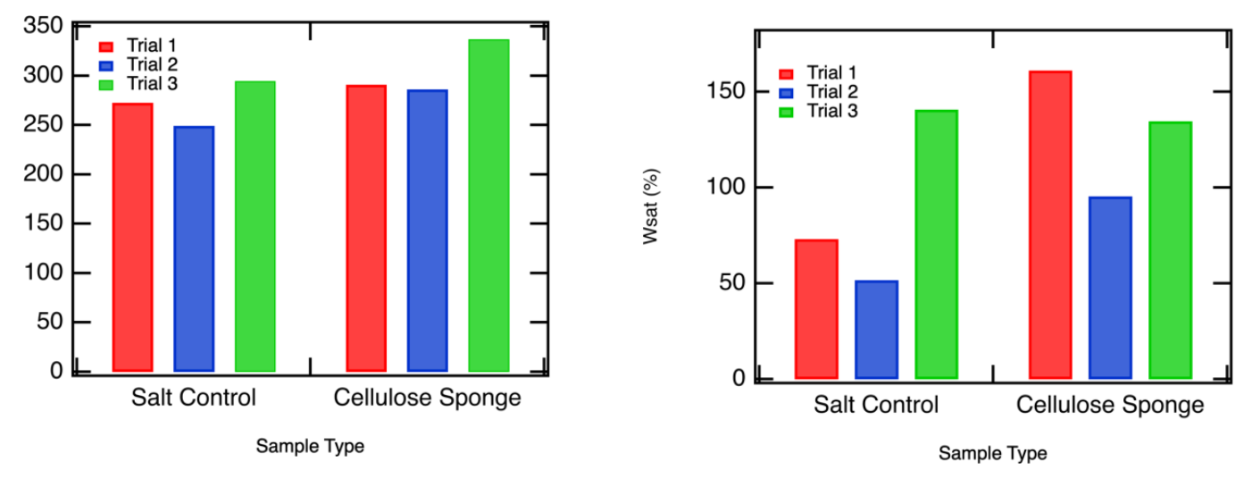


Figure 10 – Fitting constant category plot. (a) Comparing W_{sat}. (b) Comparing A_2.

6 Data Analysis

The time-lapsed moisture uptake data for both the cellulose sponge and salt control is shown in figure 4. Several observations were made. First the sponge sample exhibits higher water uptake compared to that of the salt control sample. Secondly, sponge sample absorbs moisture more rapidly. To quantify these effects in more detail, curve fit analysis is carried out. First, it is found that the curves do not fit well with a single exponential equation but rather it fits very well with a double exponential equation (Equation 1). The equation $W(t) = W_{saturated} - A_1 e^{\frac{-t}{\tau_1}} - A_2 e^{\frac{-t}{\tau_2}}$ can be thought of as a simplified version to the Langmuir-type diffusion model which is also described as a double exponential equation. To interpret the meaning behind the fitting parameters A_1, A_2, τ_1, and τ_2, the equation gives at time $t = 0$ can be considered. When, $t = 0, W_{saturated} = A_1 + A_2$.

Hence, A_1 and A_2, can be thought of as the capacity of two separate reservoirs for absorbing the moisture. τ_1 and τ_2 are time constants that relate to A_1 and A_2, respectively. It is interesting to note that τ_1 and τ_2 have different values. This suggests that there are two separate moisture absorption mechanisms that are taking place. Furthermore, τ_2 tends to show lower value than τ_1, indicating that the mechanism that is associated with A_2 and τ_2 is that of a faster process than the mechanism associated with A_1 and τ_1.

The data obtained and the analysis mentioned above make it possible to describe the two mechanisms by a simple model illustrated in Figure 6. Here there are two separate mechanisms. First (figure 6a), water absorption at the surface of the salt particle, which is in direct contact with the ambient moisture and is the primary process taking place first. Then a second mechanism (figure 6b) takes place where water at the surface diffuses into the inner core of the salt due to a moisture concentration gradient. In this model, the moisture absorption at the salt particle's surface would be a much faster process (like τ_2) than that of the water diffusion into the core of the salt (like τ_1).

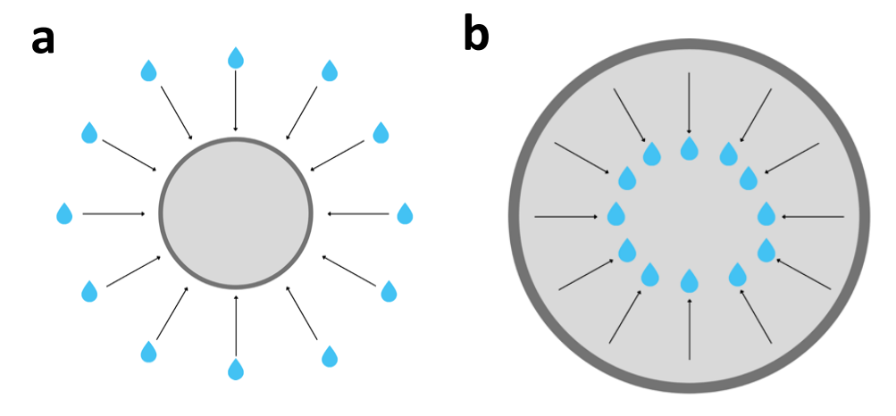


Figure 11 – First mechanism (a) and second mechanism (b) of moisture absorption.

Thus, here A_2 and τ_2 can be referred to the first mechanism of the process, the moisture absorption at the surface of the salt particle. Whereas A_1 and τ_1 refers to the second mechanism of the process, the water diffusion from the outer surface into the inner core of the salt particle. A_2 can be defined as the capacity to hold water in the first stage of the absorption process, which would be proportional to the total effective surface area of the salt particle. Whereas A_1 would correlate to the total absorption capacity of the inner core of the salt particle. Likewise, τ_1 can be defined as the rate of completing the A_1 process and τ_2 can be defined as the time constant of the A_2 process which is inversely related to the rate.

7 Interpretation

This phenomenon is best explained using the Kelvin equation (equation 2). P is the vapor pressure over a curved surface, P_o is the vapor pressure over a flat surface, γ is the liquid-vapor surface tension, V_m is the molar volume of the liquid, r is the radius of the droplet, R is the universal gas constant, and T is the temperature. When "liquid saturation in a solid porous media is low, it creates a concave interface between the water and the trapped gas within the pores" [2]. This concavity in the liquid surface lowers the vapor pressure of the porous media as r becomes negative, as radius is not being measured from the water droplet, making $P < P_o$(figure 12). The liquid-vapor interface in the cellulose sponge also may be concave given that the round pores force the water droplets to form a concave surface as shown figure 13. Liquid-gas interface as the sponge pores allow air to pass through. Deliquescence occurs when the vapor pressure of the liquefied solution is lower than the partial pressure of water vapor in the air. Upon further lowering of vapor pressure, the salt will be forced to absorb more moisture. It becomes more susceptible to higher water vapor pressure in the atmosphere and tend to equilibrate. Furthermore, a concave surface means there are more surrounding molecules due to larger surface area; this leads to stronger intermolecular attractions which attract water molecules from the air. Subsequently, it will theoretically absorb more water compared to the flat surface obtained in the salt control.

Figure 13 can be referred to explain the quicker rate of the cellulose sponge. Its microscopic pores minimized agglomeration, exposing more surface area and ultimately quickening the rate of reaction.

$$\ln\left(\frac{P}{P_o}\right) = \frac{2\gamma V_m}{rRT}$$

Equation 2–Kelvin Equation

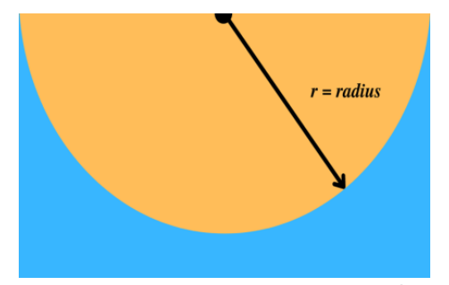


Figure 11–Negative radius

Figure 12–Concave water surface in sponge

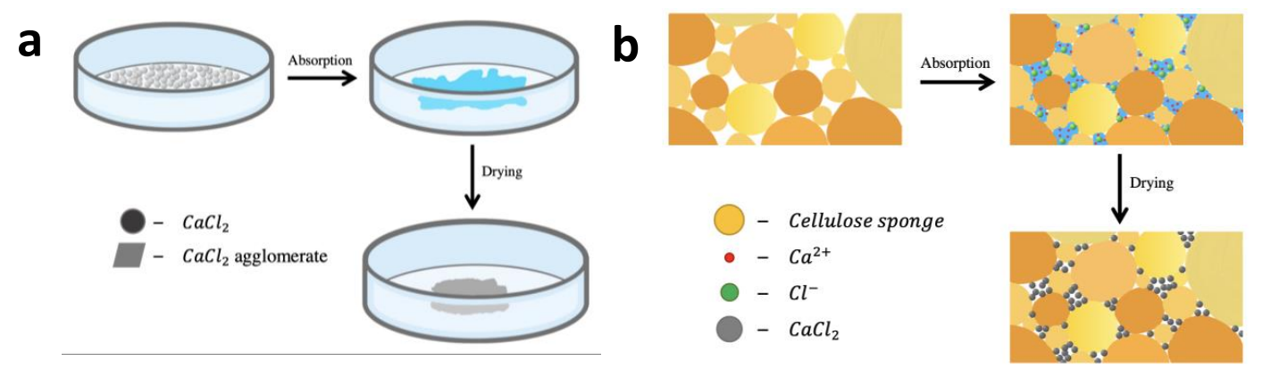
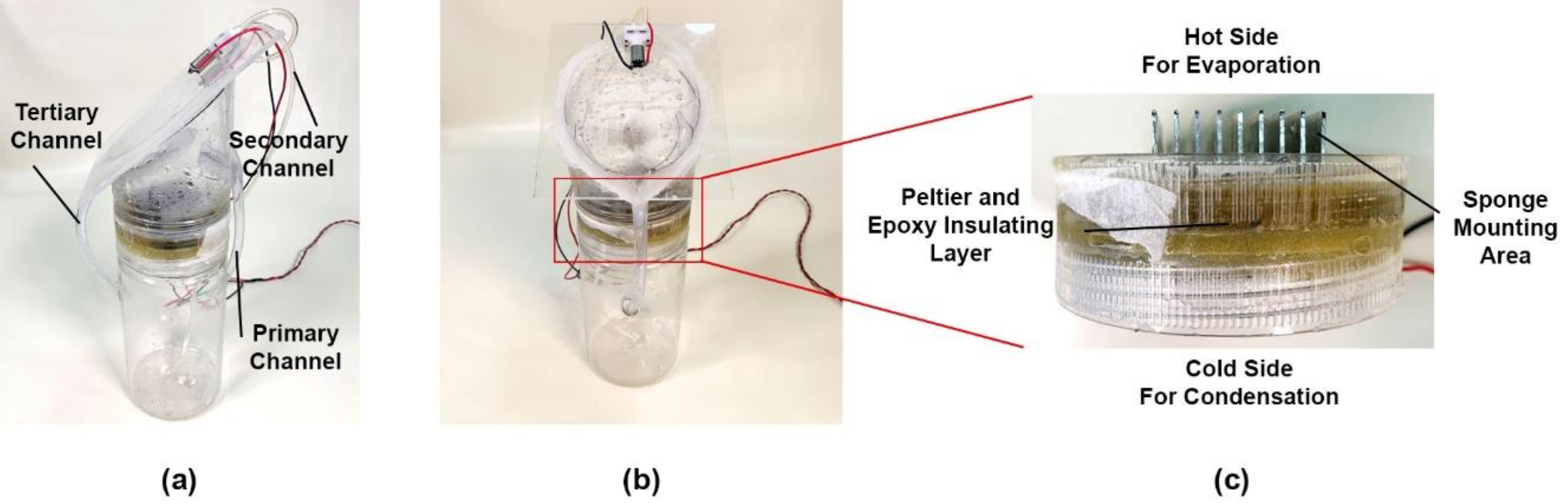


Figure 13– Modelling Agglomeration. (a) Salt control. (b) Cellulose sponge

8 Clean Water Generator Prototype



(a) (b) (c)

Figure 13 – Prototype of the clean water generator for recovering the absorbed water from the salt sponge absorber. Operations: single peltier module in a chamber of 8 cm diameter. Uses 9V, 2A and generates clean water at a rate of 5 mL/hour,

9 Conclusion

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 ºC 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.

Acknowledgments & References

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