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Article

Leveraging E-Waste to enhance water condensation by effective use of solid-state thermoelectric cooling

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SUMMARY

Water scarcity affects upwards of a billion people worldwide today. Multiple cities, such as Cape Town, Mexico City, Melbourne, and Jakarta have been threatened by water crises in the past. However, these cities are perfect for harnessing the power of water condensation. Fog nets and condensation towers have been used as water condensation devices, but these mechanisms are expensive, require preexisting infrastructure, and need certain geographic features to function. This project leverages the potential of capturing humidity to build a high-efficiency water condensation device that can generate water and be used for personal and commercial purposes. In addition, the device is portable, environment-friendly, inexpensive, scalable, and can be incorporated into existing water storage infrastructure. The device uses the principle of solid-state thermoelectric cooling and the Peltier effect to function. The Peltier effect is based on the phenomenon that when changing electric currents are applied between the junctions in a thermocouple, it causes a change in temperature. Change in temperature causes one of the junctions in the thermocouple to heat and another junction to cool. Thermoelectric modules can be packaged as part of a device that at room temperature causes cooling, thereby causing effective water condensation. This compact environment-friendly device would have low power requirements, which would potentially allow it to utilize renewable energy sources and collect water at the most needed location.

INTRODUCTION

Because 785 million people lack even a basic drinking-water service, a mechanism is needed to increase access to water throughout the day and night in an affordable and environmentally friendly way (1). One way this can be achieved is through condensation of water from humid air.

Traditionally, fog nets and condensation towers have been used as water condensation devices. Although these mechanisms require low investment in technology, installation, and operation, they can be expensive when compared to their output, making them less optimal in the long term. Additionally, fog water collection methods such as fog nets and condensation towers require specific environmental and topographical conditions for optimal results, making their placement and reliability challenging (2). Fog nets and condensation towers are most productive in mountainous regions and areas close to the ocean. Fog nets are effective in areas with long-lasting fog on a frequent basis throughout the year and locations at least 1,000 meters above sea level. Most fog nets have been measured to perform at an average efficiency of 20% meaning large scale devices are necessary generate enough water for a family (1).

Additionally, these structures are massive and must be built outside city limits, limiting their use to suburban and rural areas. This can be a big constraint for large cities with water accessibility issues, like Jakarta and Melbourne, that are looking for new ways to acquire water to serve large populations. The infrastructure needed to collect the condensed water and transport it to residential localities could become cost prohibitive. Because of these shortcomings, fog nets and condensation towers have had limited use in small local communities. Further, they are not meant for commercial use or for portable, personal use.

There are four refrigeration techniques to produce condensation: mechanical compression refrigeration, absorption refrigeration, evaporative cooling refrigeration, and thermoelectric refrigeration. Other than thermoelectric refrigeration, all other ways involve the use of a refrigerant or water (9). Oftentimes, the refrigerants are non-environmental, flammable chemicals (9). Also, traditional refrigeration mechanisms are noisy, prone to vibrations, and need specific positioning or risk failure if tilted (9). Systems that use water as a coolant are at a disadvantage in areas facing drought. Peltier systems are designed to be quiet, free of vibrations and without moving parts (10). They are small and lightweight devices that are less complex, easier to replace, and require comparatively less maintenance. Additionally, thermal cooling from Peltier systems outperform all the others as an effective way to cause reduction of temperature (10). Thermoelectric refrigeration, though effective, is premature for large-scale commercialization, but this concept and technology is apt in the scenario being considered here.

Therefore, we hypothesized that solid-state thermal cooling Peltier modules would lower the ambient temperature to the dew point temperature in a glass tank with sizable surface area to enhance condensation.

This project will use thermodynamic cycles for refrigeration. Cooling is caused by a change in the entropy of thermoelectric materials. The Peltier effect is a change in temperature caused by applying differing electric currents at the junctions in a thermocouple. "When the current flows through the junctions of the two conductors [of the Peltier tile], heat is removed at one junction and cooling occurs" (3). Peltier cooling modules and CPU cooling fans from computers that are disposed as e-waste can be leveraged as effective cooling materials. Therefore, this study will use thermoelectric Peltier elements as thermal diodes to bring the normal temperature (T) down to the dew point temperature (TD) in the condensation device and start a consistent cycle of prolonged periods of water condensation based on the ambient humidity. Peltier, or thermoelectric cooling (TEC) elements, are widely used in portable cooling appliances. This disposed e-waste could become a potential cost-saving source of material for the water condensation device.

This project aims to develop a way to affordably and efficiently condense water to provide water for local communities by capturing humidity in the air and converting it into water, benefiting all. This mechanism can be highly customized depending on the purpose of use. More than half of the cost of the device can be eliminated, since the essential materials needed to build the mechanism comes from electronic waste or e-waste.

RESULTS

A sample dataset of meteorological data from Reliable Prognosis, a weather news source, for Cape Town, South Africa from 2015 to 2020 was extracted for analysis (7). Statistical analysis was conducted to demonstrate that climatic conditions, temperature, and relative humidity, supported the utility of a condensation device. The results show potential to leverage the free humidity in the environment as an alternative source of water.

A set of 38,502 records (hours) was used as a sample. The data set included the following information for all hours of all days since 2015: temperature, relative humidity, and dew point temperature.

Three sets of information were derived based on the above data. The first set comprised the number of times when the normal temperature was equal to or less than the dew point temperature causing ideal natural conditions for water condensation. The second set comprised the number of times the difference between the normal temperature and the dew point temperature was 10°F or less. The third set comprised the number of times the relative humidity was 60% or more. The rationale for choosing the above two thresholds (10-degree difference between normal temperature and the dew point temperature and percent of relative humidity) was to allow for process inefficiencies. Relative humidity of more than 60% would provide ample opportunity for condensation to start faster. An average of the relative humidity of the 38,502 records was taken and calculated as 72%. An average of the ambient temperature of the 38,502 records was taken and calculated as 63°F. An average of the ambient dew point temperature of the 38,502 records was taken and calculated as 54°F. Rounding the difference of two averages, which was 9°F, the 10°F was used for the experiment. The basis was that, in most cases, a cooling to an extent of 10°F was required to reach the dew point temperature.

The analysis revealed that out of 38,502 hours, the normal temperature was equal to or less than the dew point temperature only 954 times. In all these cases, the humidity was 60 percent or more. Hence, out of 38,502 hours, there were 954 hours when the city benefitted from natural conditions that caused water condensation. As expected, these hours were mostly between midnight and 8:00 AM. These conditions existed for only 217 days out of 1600 days, and 75 percent of the hours existed in the months of May to September (**Figures 1 and 2**). There were 29,022 hours during the analysis period when the humidity was 60 percent or more. Of these 29,022 hours, there were 21,481 hours when the difference between the normal temperature and the dew point temperature was 10-degree Fahrenheit or less. These include the 954 hours when the normal temperature was equal to or less than the dew point temperature. Excluding natural conditions, there were 20,527 hours which could have been used to condense water if a device existed that could have created conditions to cause water condensation. In short, there were 20,527 opportunities lost to use a natural resource like humidity and extract water. The hours when these opportunities existed were spread across several days in all the months and during various parts of the day, making it a reliable and consistent source (**Figures 3 and 4**).

Next, we created an environment that resembled a real-life scenario and performed testing at home under controlled conditions to benchmark and compare testing results for four scenarios.

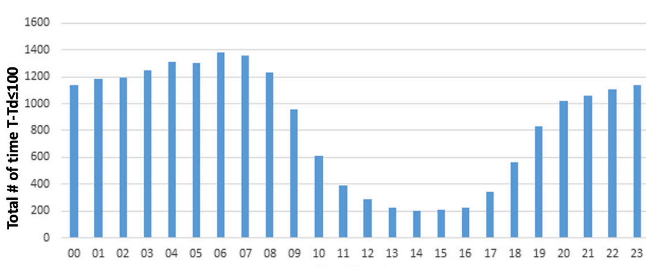

Figure 1. Total number of times T ≤ TD during every hour of the day from 2015 to 2019.

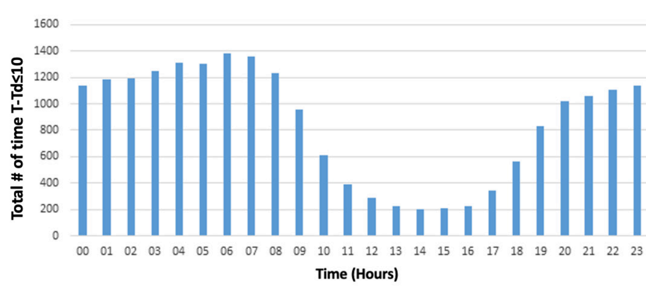

Figure 2. Total number of times T ≤ TD during a given month since 2015.

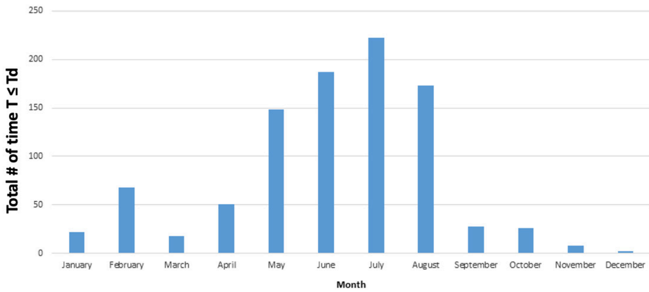

Figure 3. Total number of times T-TD ≤ 10 during a given hour of the day since 2015.

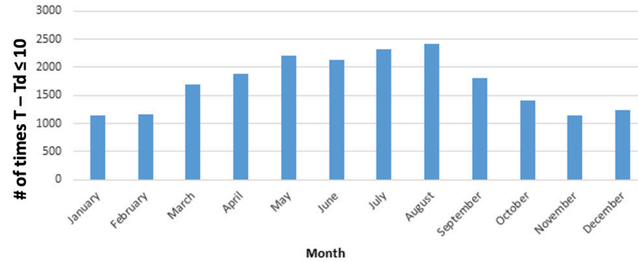

Figure 4. Total number of times T-TD ≤ 10 during a given month since 2015.

The below scenarios served as the benchmark for the later tests. Condensation was measured every 15 minutes over a 1-hour period. In the first test scenario, all independent variables were kept constant. We monitored water condensation under natural conditions with no thermo-cooling to simulate a natural as-is scenario. No condensation was observed since the ambient temperature was higher than the dew point temperature. In the second scenario, all independent variables except the total surface area were kept constant; no thermo-cooling was applied. No condensation was observed since the ambient temperature was higher than the dew point temperature. The increased surface did not have any impact on the condensation of water. In the third scenario, all independent variables except relative humidity were kept constant; no thermo-cooling was applied. Negligible condensation was observed since the ambient temperature was higher than the dew point temperature. The increased humidity did not have any impact on the condensation of water. In the fourth scenario, all independent variables except relative humidity and total surface area were kept constant; no thermo-cooling was applied. Negligible condensation was observed since the ambient temperature was higher than the dew point temperature. The increased surface area and humidity did not have any impact on the condensation of water. All four scenarios were repeated with thermo-cooling i.e. with constant reduction on temperature by the Peltier cooling module. The goal of this series of tests was to simulate the conditions of a working device.

When the Peltier cooling module was turned on, there was a consistent drop in the temperature inside the glass tank. The initial temperature at the start of the test was 82°F. The thermo-cooling was effective in dropping the temperature to the dew point temperature, which was 75°F. It took about 20 minutes to reach the dew point temperature. After 20 minutes, early signs of water condensation were visible. At the end of the one hour, about six ounces of water were collected with the base surface area exposed for condensation. As the surface area exposed for condensation was increased by about 35%, the quantity of water collected was eight ounces. A similar correlation was also observed when the relative humidity percent was increased (i.e. increase in the relative humidity caused an increase in the quantity of water collected). The testing results summary also confirmed that the Peltier module caused enough cooling and helped reach the dew point temperature. Condensation was observed when the dew point temperature was reached (**Figures 5 and 6**).

DISCUSSION

Based on the observed water collection, a standard device would conservatively be able to collect 78 ounces in a day if the device were run for 9 hours. The Constitutional Court of South Africa has quantified that 42 liters or 11 gallons of water is needed to meet the basic needs of 1 person. However, the device is meant to collect water for drinking purposes, which

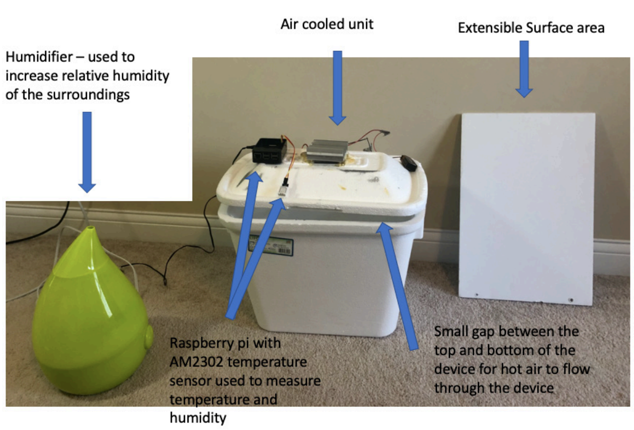

Figure 5. Photograph of testing setup.

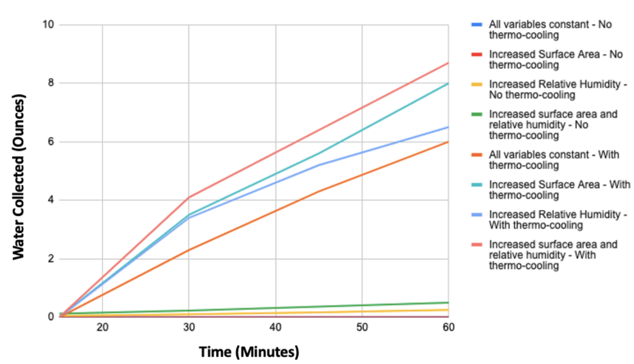

Figure 6. Condensation over time in different testing conditions.

is only about half a gallon. Based on this need, one device would be needed to collect the required drinking water for one person. As the surface area of the device increases, it will become more economical and can serve multiple people.

We hypothesized that if solid-state thermal cooling Peltier modules are used to lower the ambient temperature to the dew point temperature in a glass tank with sizable surface area, enhanced condensation would be observed. Through testing, the hypothesis was supported as water was generated using solid-state refrigeration.

Through the analysis of the data, a potential source of reduction in efficiency of the device was found. The most effective times to cool water, in the area where testing occurred, is from April to September (**Figure 3**). However, in regions such as Cape Town, these are the wet winter months and often have less sun exposure. Additionally, the hours where the dew point temperature and temperature were the same or within 10°F was primarily from 12:00 A.M. to 9:00 A.M. The average sun curve during midwinter in Cape Town shows that the sun rises at around 8:00 A.M. and sets at 4:19 P.M. (8). This means about eight hours of sunlight is available. The device will not have immediate power as the unit will run most of the night, so a battery is required to supply energy. During testing, the power requirements of the device were measured. It was deciphered that with a singular 9-volt battery the Peltier tile could run for 11.3 hours, and the CPU fan with a 9-volt battery could run for 21.25 hours. This means that the device would only require two rechargeable 9-volt batteries that are charged by solar panels. Assuming that a single cell in a solar panel generates 0.5 volts, a 40-cell solar panel that generates approximately 20 volts per day would be sufficient for the power needs of the device.

Additionally, a comparative analysis of available E-Waste and number of devices needed for Cape Town was performed. For the example of Cape Town, the city has a population of 433,688 people. One person would require one unit of the current prototype, which equals 433,688 units. This would mean approximately 433,688 solar panels and double the number of 9-volt batteries are required. The device does hinge on the fact that E-Waste Peltier tiles are accessible. Though there are not specific numbers for how many computers with Peltier tiles are disposed of each year, 7 million tons of heating and freezing equipment were recycled and daily 142,000 computers were recycled, which means that at least some portion of the Peltier tiles could be sourced through E-Waste (2). Additionally, the product utilizes solar energy, but depending on different regions the power of the device is customizable. In large cities where electricity is cheaper, the device could be plugged in, or in cities where wind energy or hydropower are more readily accessible, those could be used to power the device.

Although the device can generate 78 ounces of water per day, there are some limitations to the device. Firstly, weather conditions will affect the function of the device. For example, after heavy rains, this device would be able to generate significantly more water. However, in regions plagued by drought, the device would not be able to generate as much water. Without testing in those specific regions, it is hard to estimate the amount of water that can be generated, but combining this testing and the historical Cape Town weather data used, it can be estimated that during off-months, September through January, the efficiency of the device will drop 50%. Although the device will be affected by off-months, during the night from approximately 8 P.M. to 8 A.M., the device will still run at peak efficiency as the relative humidity is high enough for condensation occur. If the weather conditions are not ideal and the device runs at 82% efficiency, it would still produce 64 ounces of water, meeting the recommended amount of daily drinking water.

An advancement in future iterations of the prototype would be the use of metal organic frameworks (MOFs) which are organic-inorganic hybrid compounds that are crystalline and highly porous in nature. MOFs have pores with diameters less than 2 nanometers, and hence are referred to as microporous materials. The porous nature of the MOFs helps them build extremely high surface areas. So much so that 1 gram of a MOF could have surface area of 15 million square inches or upwards, which is more than the area of 2 football fields (6). MOFs possess water adsorption (not absorption) properties that provide hydrolytic stability and make them less reactive with water. MOFs have been tested to capture as much as 200% water of their own weight (6). An improved metal organic framework, hydrophobic MOFs, can not only capture and store water due to their large surface area but are effective in releasing water when heated. This is a viable option for the product, as during the night, condensing water is most effective. This means the MOF's could collect the water the unit generates through the night and release it in the morning when the temperature rises.

MATERIALS AND METHODS

A glass tank was used to collect water. One Peltier Thermoelectric Cooling Module with the following specifications was used for thermo-cooling: 15 volt, 6-ampere and Melcor type: CP1.4-127-06L unit with two 70mm, 2,900 RPM CPU cooling fans, which move about 18.58 cubic feet of air per minute. An aluminum heat sink was used for better heat dissipation. A Raspberry Pi 3 was used to run the python script that provided real-time data on the temperature and humidity. A temperature and humidity sensor (AM2302/DHT22) that uses a capacitive humidity sensor and a thermistor to measure the surrounding air was used to measure the temperature and humidity. The sensor can be used for 0–100% humidity readings with 2–5% accuracy and can be used for -40 to 80°C temperature readings positive or negative 0.5°C accuracy.

Actual testing of the device was performed to support the hypothesis. All the test cases were performed with an initial starting temperature of 82°F. This will be referred to as the base temperature. The base humidity was maintained at 70%. An increased humidity of 80% was used for those test cases that measured the impact on condensation when ambient humidity changes. A glass tank (22 in x 12 in x 13.5 in) with base surface area of 1182 square inches was used. Ten rectangular prisms (1 in x 1 in x 10 in) and an additional total surface area of 400 square inches were used to test scenarios of increased surface area. Quantity of Water Collected was measured for all the test scenarios. Dew point temperature in degrees Celsius was calculated using T – ((100 – RH)/5), where T is observed temperature, and RH is relative humidity in percent.

Relative humidity, temperature, dew point and total surface area were the independent variables in the experiment. Rate of water condensation was the dependent variable. Time for ingestion of steam was the control variable.

An important concept in consideration for the solution is the dew point temperature, which "is the temperature the air needs to be cooled to (at constant pressure) in order to achieve a relative humidity (RH) of 100%" (4). The dew point is the temperature to which air must be cooled to become saturated with water vapor (5). The third important concept is the exposed surface area. Surface area is a one of the most important factors since humidity needs a surface to condense. Lack of a large area can become a huge constraint for compact portable water condensation devices. The laws of thermodynamics can help solve the problem of reducing the normal temperature to the dew point temperature to create optimal conditions for condensation, but the lack of sufficient exposed surface area would underutilize the created conditions and render the device ineffective.

The testing of the device was completed in four different scenarios to test the maximum efficiency and ideal working conditions of the device. Each measurement was completed five times, and the given data is the average of the five tests. Additionally, the varied conditions exposed the device to different climatic conditions to evaluate its use in different climates.

To complete the first scenario where all independent variables were kept constant and no thermo-cooling was applied, the temperature was set to the constant 82°F and the humidity was maintained at 70%. In the second scenario, all independent variables except the total surface area was kept constant and no thermo-cooling was applied. In this test, the temperature was set to 82°F and the humidity was set to 70%. In addition, rectangular prisms where attached to the top of the lid. In the third scenario, all independent variables except relative humidity were kept constant and no thermo-cooling was applied. In this case, the temperature was constant at 82°F and the humidity was increased from 70% to 80%. In the fourth scenario, all independent variables except relative humidity and total surface area were kept constant and no thermo-cooling was applied. Finally, the temperature was constant at 82°F, but the humidity was increased to 80% in conjunction with the rectangular prisms, which were attached to the top of the lid. These 4 scenarios were repeated, but the thermo-cooling was applied. During the tests where the thermo-cooling was applied, air channels were created for the cold air to flow through the rectangular prism, so that they total surface area would be increased.

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