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Applying Biomimetic Principles to Thermoelectric Cooling Devices for Water Collection

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Abstract

The shortage of freshwater resources in the world has developed the need for sustainable, cost-effective technologies that can produce freshwater on a large scale. Current solutions often have extensive manufacturing requirements, or involve the use of large quantities of energy or toxic chemicals. Atmospheric water generating solutions that minimize the depletion of natural resources can be achieved by incorporating biomimetics, a classification of design inspired by nature. This research seeks to optimize thermoelectric cooling systems for use in water harvesting applications by analyzing the different factors that affect surface temperature and water condensation in TEC devices. Further experiments will be directed towards developing a robust, repeatable system, as well as an accurate measurement system. Surface modifications, device structure and orientation, and power generation will also be studied to better understand the ideal conditions for maximum water collection in thermoelectric cooling systems.

Keywords: atmospheric water generation, biomimicry, dehumidification, fog harvesting, Peltier effect, surface temperature, surface wettability, sustainability, thermoelectric cooling, water collection

1. Introduction

1.1 Shortage of Freshwater

It has become evident that because of a steadily increasing demand, the depletion of freshwater resources is putting the sustainable development of human society at risk. In its most recent annual risk report, the World Economic Forum lists water crises as the largest global threat in terms of potential impact (Mekonnen, 2016; World Economic Forum, 2015). Global water demand is largely influenced by population growth, urbanization, food and energy security policies, and macro-economic processes such as trade globalization and changes in consumption patterns (WWAP, 2015). Other factors that determine water scarcity include the geographical and climatic variations of water resources (Savenije, 2000). 85% of the world population lives in the driest half of the planet, where water scarcity is the highest, and an estimated 783 million people do not have access to clean water (United Nations, 2013). Transporting water over long distances via pipeline or tanker produces greenhouses gases in the construction, transport, and treatment of the water, and costs an average of $9 billion per year to maintain based on a 200 GL/year delivery over a distance of 4,000 km (Commonwealth of Australia, 2010). According to the Watereuse Association Desalination Committee, desalination plants require an average of 100 MWh of power to produce 10,000 m^3 of potable water per day, which is limited to coastal communities (Watereuse Association, 2011).

1.2 Background Work

There are alternative methods to mitigate the freshwater crisis in arid ecoregions that revolve around extracting moisture from the air. The two main classifications of atmospheric water generation (AWG) technologies are active and passive. Active AWG technologies require the use of energy, and typically include a motorized compressor or pump to convert from vapor to liquid (Milani, 2012). Passive designs do not cause or perpetuate the depletion of other limited natural resources such as coal, oil, and natural gas (Jackson, 2012). The focus of existing research has been on surface wettability and geometrical structure, and less about surface temperature as a method of biomimetic AWG.

1.3 Research Focus

The purpose of this research is to investigate the factors influencing surface temperature as a method of inciting water condensation. The rest of the article is presented as the following: In sections 2, active, passive, and combined water collection mechanisms are discussed. In section 3, an experiment setting to test the performance of a Peltier system is explained. Results followed by a discussion that combines these concepts using thermoelectric modules including a plans for future works in this field are presented in section 4 and 5, respectively.

2. Water Collection Approaches

2.1 Active Water Collection

Condensation will form on any object when the temperature of the object is at or below the dew point temperature of the air surrounding the object. Dew point temperature is defined simply as the temperature at which water vapor, when cooled, will begin to condense to the liquid phase. During the process of condensation, water molecules lose some of the latent heat that was added during the evaporation process, which then warms the surrounding air (Wahlgren, 2001). Many active AWG technologies employ cooling surfaces to remove this heat and condense water vapor in the ambient air. This can be done either by using a circulating media called a refrigerant, or an electrical current.

2.1.1 Refrigerant-based Cooling Systems

Refrigerant is a substance which is used as working fluid in a thermodynamic cycle (Kaushik, 2016). They absorb heat from one area and reject it into another, usually through evaporation and condensation. Based on refrigerant types, cooling system techniques can be further sub-categorized into the following: vapor compression refrigeration (VCR), vapor absorption refrigeration (VAR), and active magnetic regeneration (AMR).

Typical refrigeration systems are based upon the vapor compression refrigeration (VCR) cycle. In a VCR cycle, a liquid refrigerant enters a compressor in the form of vapor, and is cooled into a liquid state. The refrigerant then returns to the evaporator to begin a new cycle. VCR systems have a high coefficient of performance (COP) compared to other AWG techniques, but have many disadvantages. Compression systems are complex, can be difficult to maintain, and require a substantial amount of electrical energy to operate (Zubair, 1994). Furthermore, the refrigerant currently used in VCR systems, R-134a, has a high potential of ozone layer depletion and is not recommended for long-term use (Brown, 2002).

Vapor absorption refrigeration (VAR) systems lack a mechanical compressor. The only working part in this system is the pump, which works to heat the refrigerant into a vapor and drive it to the condenser at high pressure and temperature. The cycle is complete once the heat is rejected to its cooler surroundings and the liquid refrigerant returns to the absorber. VAR systems require less electrical energy than VCR systems, but the COP of vapor absorption refrigeration systems is poor. The refrigerant used in VAR systems is usually an ammonia-water or lithium-bromide-water solution, which, although circulates with greater efficiency than compressed gas, can be toxic and corrosive (Milani, 2012).

The principle of active magnetic regenerator (AMR) systems involve the use of magnetic elements to propel a solid, magnetic refrigerant through a cycle that adds/removes the magnetic field to create an increase/decrease in temperature. AMR systems are not harmful to the environment and have a high COP compared to VCR and VAR technologies, but are expensive and 2 to 3 times heavier than other refrigerant-based cooling systems (Gschneidner, 2002).

2.1.2 Thermoelectric Cooling Systems

Thermoelectric cooling devices create a heat flux between the junction of two materials to condense water vapor without the use of refrigerants. The thermoelectric, or Peltier effect, occurs when heat from a current is interchanged between two polar conductors (Tellurex Corporation, 2010). The Peltier effect most strongly manifests itself in semiconductor circuits, composed of n-type and p-type semiconductors commonly made from Bismuth telluride and its alloys. The direction of the electric field causes electrons in the n-type and holes in the p-type to flow towards one another. When electrons pass through this boundary, an electron enters the p-type and takes the place of a hole. This recombination causes heat to be released on one side of the TEC device and absorbed on the other, depending on the direction of the electric current. TEC modules are compact, low maintenance, cost-effective, free of moving parts, and do not pose any major risk to the environment; however, they have the lowest COP compared to other active AWG technologies, and have seen little improvement in their thermal efficiency over the years.

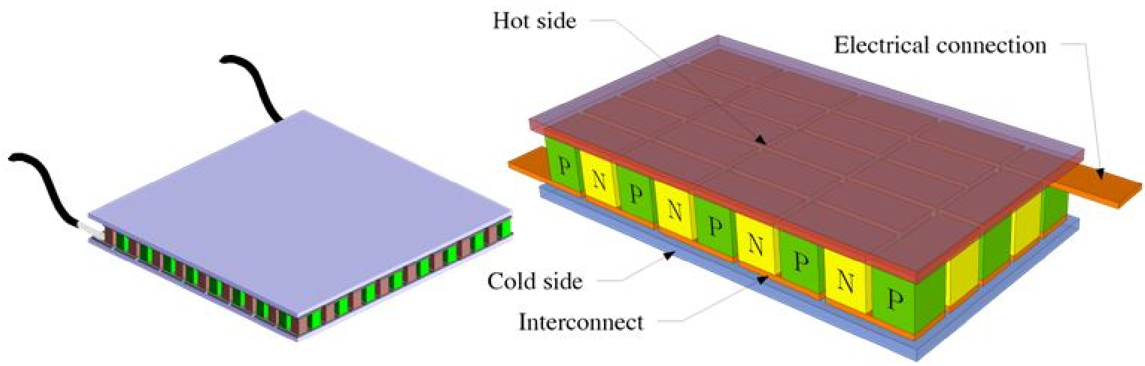

Figure 1. n-type and p-type semiconductors within a thermoelectric cooling device

2.2 Passive Water Collection

Passive AWG designs can be achieved through biomimetic principles, which minimize damage to the environment as their technologies do not require large quantities of energy or toxic chemicals. Kennedy et al. (Kennedy, 2015) defines biomimicry as a classification of design that seeks sustainable solutions to human challenges by learning from and emulating biological forms, processes, and ecosystems tested by the environment and refined through evolution. Many plant and animal species have evolved adaptations that give them the ability to attract, repel, or transport water. During the last few decades, researchers across the globe have studied these adaptations in an effort to guide the development of future AWG technologies.

2.2.1 Surface Wettability

One of the most widely researched topics in passive water collection is the *Stenocara gracilipes*, a species of beetle native to the extremely arid Namib Desert in southern Africa. The Namib Desert is completely devoid of surface water and has a highly unpredictable annual rainfall. Thick fogs along the coast provide enough moisture for a number of highly-adapted animal species, such as the Stenocara beetle, to survive (Jacobson, 1995). Also known as the fogstand beetle, this species adopts a head standing position facing the wind in order to collect fog droplets on their forewings (White, 2013), which are coated with a combination of hydrophilic bumps and hydrophobic grooves. Droplets accumulate on the bumps until they are large enough to coalesce and roll down into the waxy grooves and into the beetle's mouth. Several experiments have been modeled after these hydrophobic and hydrophilic micro- and nano-structures in an effort to improve surface wettability and attain higher yields of water.

Figure 2. *Stenocara gracilipes*

Dorrer et al. (Dorrer, 2008) conducted an experiment to test whether or not the beetle's fog harvesting ability can be attributed to the waxy and non-waxy surfaces on its back. Hydrophobicized silicon nanograss with hydrophilic circular polymer bumps were prepared, on which drops of water were deposited and analyzed at various angles. A range of drop radii between 2 and 4mm was observed during testing (Dorrer, 2008), which is comparable to the 4-5mm drop diameters that have been observed for the beetles in their natural environment range from 4-5mm (Parker, 2001).

In 2013, researchers from McGill University in Montreal tested PTFE, Al, Ti, and SS-CNT samples to better understand the wetting properties of materials as well as the effect pattern has on the Stenocara beetles' capability to collect water. To cover various surface contrast ranges, the samples were channeled, checkered, dot-patterned, or unmodified. White et al. (White, 2013) found that, although there were slight differences in the coalescence and motion of the drops on the differently patterned surfaces, no direct influence of the type of pattern on the sample was found on its water collection ability.

Pazokian et al. (Pazokian, 2012) used UV laser pulses to tailor the wetting properties of polymers from highly hydrophilic to superhydrophobic. Their results indicated that the surface wettability variations are dominantly caused by laser-induced chemical modifications, which are highly dependent on the pulse energy and duration (Pazokian, 2012). The ability to tune the wetting properties of materials using chemical and laser treatments has been achieved by NBD Nanotechnologies, a startup company inspired by the Stenocara beetle that claims to have mastered surface wettability using their formulated coatings and additives. Supported by the United States Department of Agriculture in a SBIR Phase II grant, NBD has piloted its fog capture technology in various sites in California in an effort to prove efficacy of an alternative passive water resource (NBD Nano, 2016). During testing, NBD demonstrated approximately 3-5 fold enhancement of water harvesting from fog using their coated mesh, compared to traditional non-coated fog nets. At maximum, above 5 gallons of water from a single $1m^2$ fog net can be collected per day (USDA, 2015).

Some plant species, such as the lotus, exploit their natural hydrophobicity for self-cleaning. Although many other plants have superhydrophobic surfaces with 150º+ contact angles, the combination of optimized features such as the surface topography, robustness, and unique properties of the epicuticular wax contribute to the lotus plant's exceptional stability and water repellency (Ensikat, 2011). The nanostructures on their surfaces are coated with wax crystals approximately 1nm in diameter, which makes the surface at the nanoscale rough, and therefore more hydrophobic (Kalaugher, 2002). Most of the artificial surfaces developed thus far have used various polymers during synthesis; Latthe et al. (Latthe, 2014) believes that future superhydrophobic research should be directed towards organic, polymeric superhydrophobic coatings, as they show good adhesion and can last longer with high mechanical durability and optical transparency.

Figure 3. Surperhydrophobic surface of the lotus plant

2.2.2 Geometrical Structure and Arrangement

In other experiments, researchers have studied the effects geometrical properties have on the ability of different plant species to collect water, particularly those found in deserts and ecoregions where there is minimal rainfall. Many species of plants are self-sustainable, and can survive some of the world's most extreme climates due to structural adaptations that allow them to consume vapor from the air in the event of a drought.

According to a study conducted by Martorell and Ezcurra (Martorell, 2006) on the functional and evolutionary approach to fog-harvesting, plants that use fog as an important water source frequently have a rosette growth habit. Many plant species that belong to the agave, bromeliad, and succulent families rely on the funnels that form from the rosette pattern to conduct water to the plant's roots. Ebner et al. (Ebner, 2011) tested several species of this type of plant using models with the purpose of identifying any correlation between leaf surface area/density, and water collection abilities. It was found that high positive interception efficiencies corresponded to the models with long, narrow leaves, while low values corresponded to the models with wide, thick, fleshy leaves (Ebner, 2011).

Figure 4. Agave species with long, narrow leaves

Studies done on *Stipagrostis sabulicola*, an endemic grass species found in dune fields of the central Namib Desert, also show that narrow leaves with a high length-to-width ratio are the most suitable for fog harvesting (Roth-Nebelsick, 2012). According to Jones (Jones, 1992), there is a significant evolutionary trend towards the so-called "narrow-leaf syndrome" in xerophytic rosettes and other plants that grow in fog-rich ecoregions. Furthermore, fast winds reduce the envelope of slow-moving air around the leaves and drive droplets into the leeward side of the leaf, where no droplets would normally collide. Since wind speed increases with distance from the ground, structures should be placed high above the ground as observed in some species of Yucca and Nolina (Jones, 1992). Therefore, the following factors should characterize efficient fog harvesters: long, narrow structures that are both large in number and placed at a higher distance from the ground.

2.2.3 Surface Temperature and Thermoregulation

The internal generation of heat to maintain body temperature is usually associated with birds and mammals. Thermoregulation also occurs in some plant species in order to enhance rates of pollination and maintain stable tissue temperatures (Watling, 2008). A critical requirement of plants is that they maintain a consistent leaf temperature as close as possible to the optimal temperature for growth in variable environmental circumstances. Thermal stability is achieved by increasing the rate of heat production in proportion to the decrease in ambient temperature (Seymour, 1996). The thermoregulatory processes in plants are only thermogenesis, the generation of heat in the face of cooler ambient temperatures.

Conversely, Ishay et al. (Ishay, 2003) observed that hornets or wasps of the subfamily Vespinae have body temperatures that are sometimes significantly lower than the ambient temperature. This suggests that the hornets posses a natural thermoelectric heat pump that allows for internal cooling. The hornet cuticle has a layered cellular microstructure that is strikingly reminiscent of the alternating n-type and p-type microstructures used in the fabrication of commercial TEC devices (Ishay, 2003). Ishay et al. believes that this is the first instance where a natural biological heat pump has been observed in a living creature, and also believes this is the first time that a thermoelectric effect is deemed to play a role in the physiology of a living creature. It has not yet been identified whether or not thermoregulating species use their natural abilities for the purpose of collecting water, although, as mentioned above, the formation of condensation is highly dependent on surface temperature. The continuation of this research may contribute to the advancement of bio-inspired AWG solutions.

2.3 Combining Passive and Active AWG Techniques

In order to develop an economical, cost-effective AWG system that can be used on a large scale, one must consider both the advantages and disadvantages of the technologies currently used today. From an ecological perspective, biomimetic AWG methods are preferred due to their sustainable nature and low maintenance. However, as mentioned above, the performance of some biomimetic technologies such as array structure and surface modifications are maximized only when air flow, such as wind, is present. For active AWG technologies, thermoelectric cooling systems are an attractive option due to their being small, motionless, noiseless, and cheap compared to other active AWG methods. Regarding energy efficiency, another advantage of the TEC device is that they work by DC electrical current which makes the integration with solar PV systems possible (Milani, 2012). However, a major challenge in the cooling system based on the Peltier effect is temperature control and consistency. Hence, the focus of this research is on optimizing surface temperature in thermoelectric cooling devices as a means to incite the formation of condensation.

3. Method

3.1 Identifying the Factors that Affect Surface Temperature in a TEC Device

The temperature difference generated between the hot and cold sides of the TEC device depends on many factors such as ambient temperature and humidity, the nature of the thermal load, optimization of voltage and current delivery to the TEC device, and optimization of heat sinks (Muñoz-García, 2013). A TEC device has a maximum heat pumping capacity Qmax if the temperature difference between both sides is 0ºC. The current and voltage associated with Qmax are Imax and Vmax, respectively. ΔTmax is the maximum temperature difference across the device, when absolutely no heat is pumped. However, this maximum value is only theoretical and is never reached in a thermoelectric application (Meerstetter Engineering, 2017). According to Meerstetter Engineering, there is always a trade-off between Qmax and ΔTmax; at Imax either Qmax is zero and ΔTmax is at its maximum, or vice versa. It should be noted that an increase in thermal load causes a higher rate of electron recombination to occur, decreasing the optimal performance of the device. Performance can also be compromised if a heat sink is not employed in a thermoelectric cooling design. When cooling a thermal load, some form of heat sink must be used to dissipate collected heat into another medium, such as air or water (Tellurex Corporation, 2010). Without such provisions, the TEC device will be vulnerable to overheating; once it reaches the melting point of the solder, the unit will be destroyed.

3.2 Testing the Factors that Affect Surface Temperature in a TEC Device

For this application, it is required that the temperature of the cold side remains below the atmospheric dew point, and above freezing temperatures to allow for the formation of condensation. An experiment was conducted using a 40 mm² TEC1-12706 thermoelectric module made from aluminum oxide (Thermonamic, 2015) to test for consistency in surface temperature over time at a constant voltage. The TEC device was attached flat against a 107 mm² aluminum heat sink, under which a cooling fan was positioned. The system was then placed on a small support structure to allow for air circulation. The 12 V power supply that connected the cooling fan and TEC device was set to maximum voltage. Five testing points on the surface of the TEC device were selected: one on each corner, and one in the center. Voltage was applied to the TEC system for 15 min, and the surface temperature of each point was recorded at 1-min intervals, using both a thermocouple and an infrared thermometer.

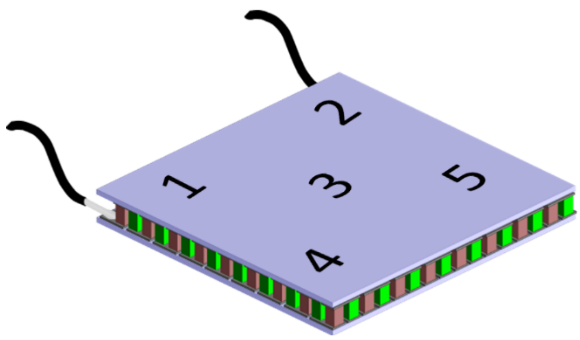

Figure 5. Temperature testing points on the TEC device

4. Results

The following chart illustrates the variation of temperature, measured with a thermocouple, over time for different measurement spots.

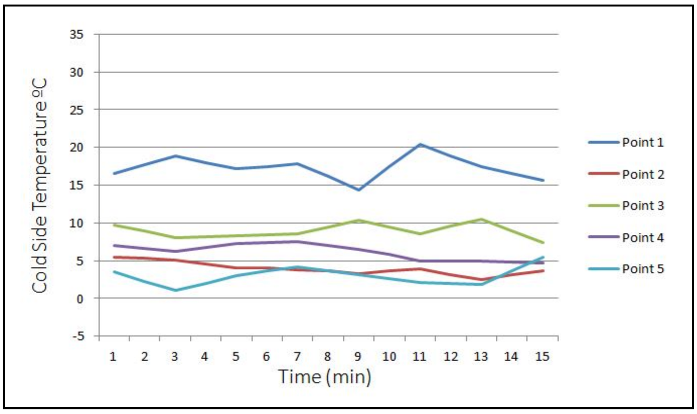

Figure 6. Cold side temperature taken with thermocouple. Ambient temperature 23ºC, ambient humidity 56%, dew point 14ºC

Although surface temperature remains fairly consistent at each of the five points, data shows temperature differences between the point locations. However, it should be noted that the formation of condensation was observed on the cold side surface, and remained in a liquid state throughout testing. This indicates that, on average, the surface temperature remained above 0ºC and below the atmospheric dew point of 14ºC; data collected using the thermocouple instrument reflects these preconditions for condensation.

5. Conclusion

Together, the findings discussed in this article establish convergence in a vast range of water harvesting methods and can serve as a guide for future sustainable AWG designs. The results of this experiment support previous works by others (Almusaied, Z. and Asiabanpour, B. 2017) and show capacity for producing water by utilizing surface temperature in thermoelectric cooling devices. However, further experiments are necessary to better understand the conditions that support consistent behavior in a TEC system when attempting to induce the formation of water. A robust, repeatable system, as well as a more accurate measurement system will be needed in order to develop reliable temperature control procedures that will keep the surface temperature below dew point and above freezing temperatures. An in-depth study between surface modifications/device layout and condensation formation/dew drop behavior will also need to be conducted in order to exploit biomimetic principles and improve the water collection abilities of thermoelectric cooling devices. Based on these studies, further experiments will be conducted to measure the water generation output and determine the efficacy of this method to produce potable water on a larger scale. Utlizing renewable energy such as solar energy will also impact the environment positively by producing fresh water without any additional consumption of non-renewable energy (Asiabanpour et. al. 2017). The estimation of the fresh water is around 1% of the total water on our planet. Capturing and utilizing atmospheric water, which is estimated to be around 3095 cubic miles, can be a potential sustainable solution to the growing water demand problem (Almusaied & Asiabanpour, 2017). The most common applied technology in this field during the last few years is VCR. The power consumption associated with this technology is still high. The use of renewable energy to supply the AWGs can be a viable environmental solution to this problem. Also, a further development to reduce the power consumption of the AWG will be a game changer in this field.Continuing this research will allow for the advancement of AWG technologies that have the potential to benefit communities in developing countries while causing minimal economic and environmental strain.

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