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Water Harvesting from Fog Using Building Envelopes – part II

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Abstract

Fog harvesting stands out as a simple and inexpensive form to produce drinkable water from alternative sources, when compared to other available techniques. This paper presents results from a set of experiments performed on radiative condensers, deemed as a promising system to be integrated in building envelopes, following a literature review on fog condensers presented in a previous work. An analysis of condensation potential obtained using high emissivity substrates and titanium dioxide nanocoatings is presented, as well as the influence of sample position and orientation, and impact of climatic variables. Finally, the role of nanotechnology in overcoming limitations of radiative systems is discussed as a means to increase harvesting efficiency with functionalized, engineered nano-patterns on collector surface. Based on biomimicry principles, nanocoatings including nanoscale 3D optimal geometries are discussed, and the use of nano-imprint technology (NIL) is proposed to massively produce nano-patterned panels with biomimetic fog capturing features.

1. Introduction to fog harvesting integration on building envelope

Water shortage has become critical in several regions of the world, which are already experiencing the first symptoms of water scarcity. Among all the available water harvesting technologies, fog harvesting has acquired importance in the last years, as a way to provide drinkable water to rural communities (Klemm *et al.*, 2012). This water source is more sustainable compared to those mentioned above, and can produce safe and drinkable water at low cost (Schemenauer, 2010). The history of water collection from humid air dates back to the ancient Greek period, in an area that corresponds to current Ukraine (Nikolayev, 1996). Other attempts were performed in France around the 1920s, but yields were extremely low (Beysens *et al.*, 2003). Nowadays, progresses in fog harvesting are reported in the FogQuest conference, a biennial event that provides a broad audience with accurate insights on the field. The first Fog Water Collection Manual was published in 2005 by Schemenauer et al.

Based on a review of existing fog harvesting systems presented in the first part of this work, this paper illustrates a proposal to bring the concept of water harvesting from fog into the urban environment, through the exploitation of building envelopes as potential collecting surfaces. Some experiments have been performed to assess crucial aspects affecting the possibility of including such systems in a building component. This work makes a step further in the conception of enhanced fog collection systems that integrate nanostructured surfaces to push condensation on the building envelope.

The number of successful projects on fog harvesting, as presented in the first part of this work, shows promise for the implementation of analogous systems in cities. In fact, the exploitation of envelope surfaces, both in the case of existing and new buildings, could provide large areas available for fog water harvesting. The integration of water collecting surfaces on the building envelope could help achieving sustainability objectives and supply water for specific building uses. This applies well to commercial and institutional (CI) end uses of water, where the amount needed per user is limited compared to residential use, in a ratio from 1:5 to 1:10 (Mayer *et al.*, 1999; Dziegielewski *et al.*, 2000).

Radiative condensers seem to be the most appealing system for implementation on building envelope components. Condensation phenomena taking place on the condenser surface rely solely on temperature gradient and do not require any air flow through the element. Still, wind direction and speed can affect the condenser yield (Beysens *et al.*, 2003).

2. Experimental measurements of radiative systems

As radiative systems seem to hold the most promise for application on building envelopes, an initial experimental setup was developed to assess the main variables influencing the performance of such systems. These initial tests were designed to help guide future research developments, by providing insights into key variables.

The first test consisted basically on a visual inspection of the effect of applying a titanium dioxide nanocoating on a metal surface, in terms of promotion of coalescence. The metal used was steel welding sheet (brushed), spray painted with a high emissivity white paint, Krylon Flat White #1502, with an emissivity between 0.989-0.992. The titanium dioxide based product used for the experiment is a semitransparent water-based solution, which embeds titanium dioxide nanoparticles in the order of magnitude of 10-20 nm. The coating is generally used to promote self-cleaning behavior of building façades, based on a strong hydrophilicity under the effect of ultra-violet (UV) irradiation, and a converse strongly hydrophobicity in dark conditions. The effect of enhanced surface hydrophilicity promoted by the use of a self-cleaning titanium dioxide coating is easily detected in Figure 1 b and 2 b, where the water contact angle is extremely low (values close to 0°) and thus drops tend to enlarge the surface occupied on the coated area. The product was supplied by Nextmaterials, a company specialized on developing nanotech coatings for air and water purification purposes. Two similar samples were used, one with a titanium dioxide coating, the other a control sample with no coating. The samples were placed horizontally, with a 2% tilt to promote dripping. Observations were carried out between 4am and 6am, the coldest nighttime period on June 2015.

The titanium dioxide coating displayed an improved capacity to promote droplet coalescence, in relation to the uncoated sample. Figures 1 and 2 show images of the metal samples under study, which illustrate that phenomenon. In both figures, the coated sample is on the right, while the left image shows the uncoated sample. It can be observed that the coating on the right promoted the formation of larger droplets of condensed water, which in turn promotes the movement of water across the tilted surface of metal, for collection at the bottom (Lv *et al.*, 2015). This is particularly relevant because if the water does not move down, it will evaporate before being collected, namely due to the effect of wind on building surfaces.

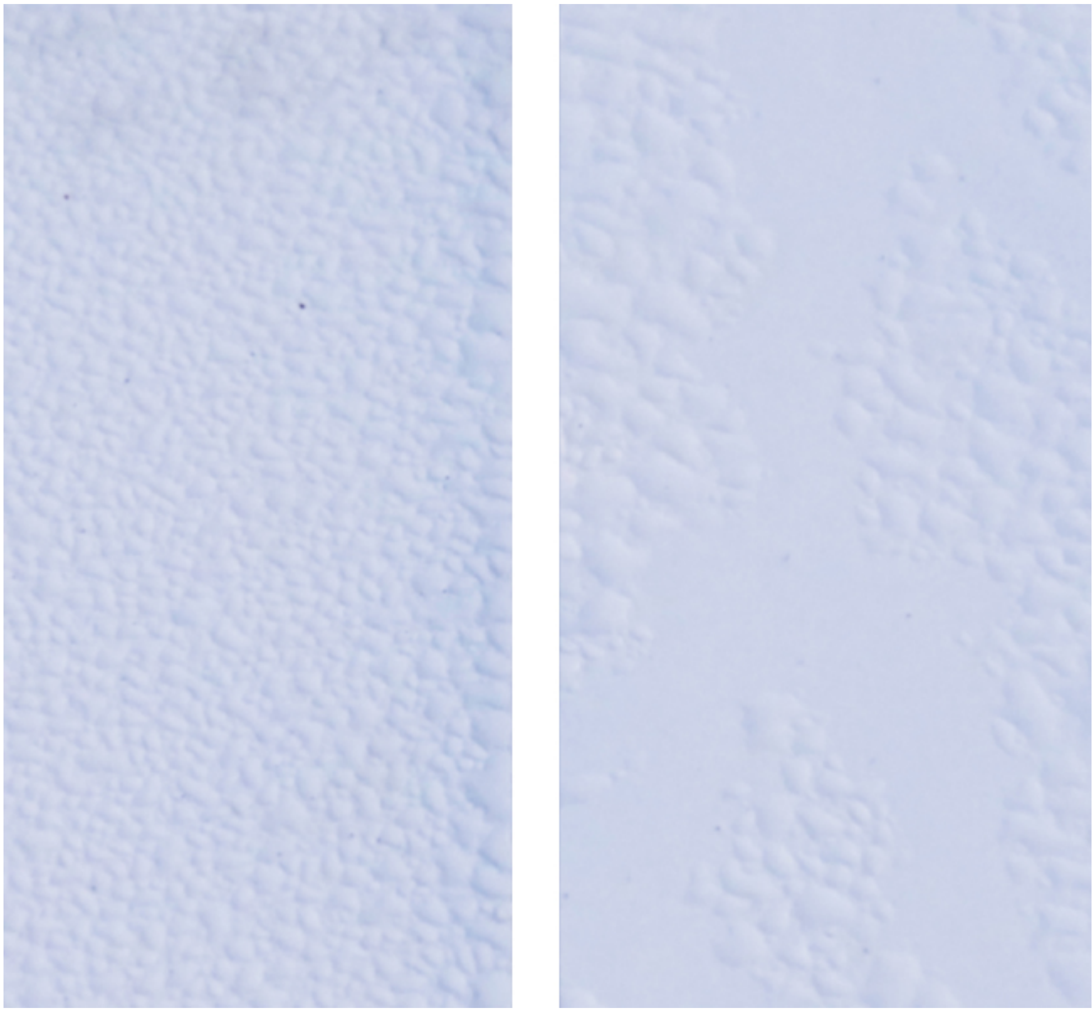

Figure 1. Left: White metal uncoated sample 1. Right: White metal coated sample 1, with titanium dioxide nanocoating. The coating promotes the formation of larger droplets of condensed water, which increases the movement of water down the tilted metal surface, for collection at the bottom.

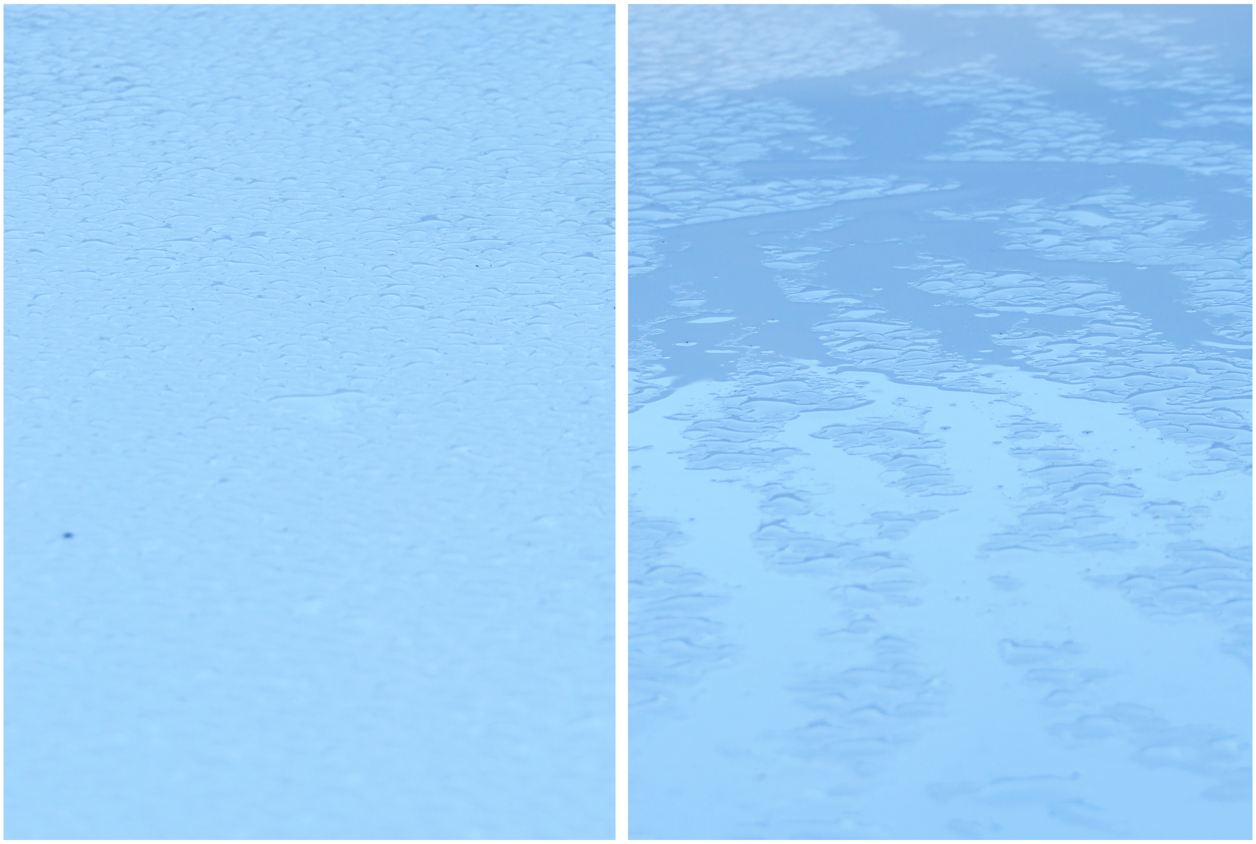

Figure 2. Left: White metal uncoated sample 2. Right: White metal coated sample 2, with titanium dioxide nanocoating. The coating promotes the formation of larger droplets of condensed water, which increases the movement of water down the tilted metal surface, for collection at the bottom.

The goal of the following rounds of experiments was three-fold: 1) to test the effect of applying a titanium dioxide nanocoating for reducing surface temperature of building materials; 2) to test the effect of materials emissivity in reducing surface temperature; 3) to test the effect of surface tilt and orientation on surface temperature, in relation to wind speed and direction.

Two rounds of experiments were performed, in September and December 2015. The experimental set up was placed on the roof of Wurster Hall, the architecture building of UC Berkeley, California. A weather station was installed next to experimental setup, to relate measured surface temperature in the samples with air temperature, relative humidity and wind speed and direction. In the Berkeley climate there are frequent occurrences of high humidity levels, due to the advection fog carried out from the pacific coast, first into San Francisco and then into Berkeley. Figure 3 shows that high humidity levels above 90% (dark blue dots in the image) are frequent during the colder periods of the year. In general, California coastal locations are good candidates for fog collection, as regions like central and southern coastal regions of California have 266 to 317 days of fog per year, thus presenting very adequate meteorological conditions to implement fog harvesting (Hiatt at al 2012).

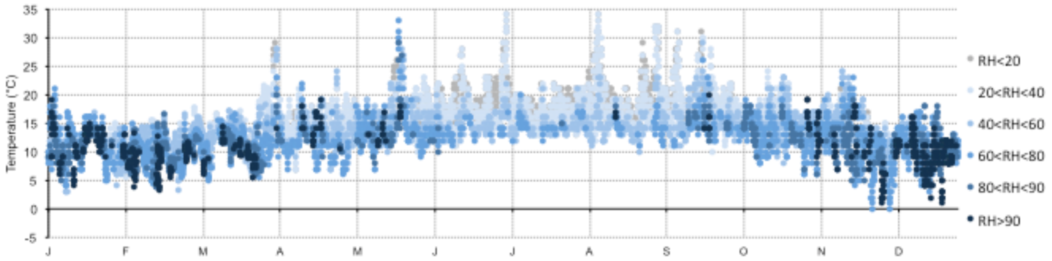

Figure 3. Annual temperature and relative humidity data from Oakland Airport, California. Distance to measurements site is approximately 11 miles.

Experiment 1 compared the performance of glass sheet and white metal sheet in terms of promotion of surface condensation. The metal used was steel welding sheet (brushed), spray painted with a high emissivity white paint, Krylon Flat White #1502, with an emissivity between 0.989-0.992. The glass used was a standard 3mm float clear glass sheet. Additionally, to test the effect of the same NextMaterials titanium dioxide nanocoating on promoting lower surface temperatures, for both materials (glass and metal), there was a sample coated with titanium dioxide, and a control sample without the coating.

Finally, we tested the effect of orientation on promotion of surface condensation. For a radiative system to succeed, the objective is to create the lowest possible surface temperatures during the night period, when condensation is likely to occur. It is thus important to maximize the exposure of the materials to the night sky, to promote the lowest temperatures in the evening. A horizontal setup was thus favored, with a minimum tilt to promote dripping. Additionally, the experimental setup included samples tilted 5° in relation to the horizontal, facing the four cardinal orientations, to relate surface temperatures with the effect of wind direction and velocity.

Results from experiment 1 are shown in Figure 4. In the legend, the first letter represents either Metal or Glass (M,G), the second letter represents Coated or Uncoated, regarding the application of titanium dioxide nanocoating (C,U) and the last letter indicates the orientation of the sample (H for horizontal, and N,S,E or W for the tilted samples).

Figure 4 shows that the horizontal white metal sample, coated with titanium dioxide, consistently achieved the lowest surface temperature. Glass samples, even if coated, were always significantly warmer (thus farther from dew point) than all other samples, due to the lower emissivity of glass compared to metal. A high emissivity material is fundamental in promoting condensation.

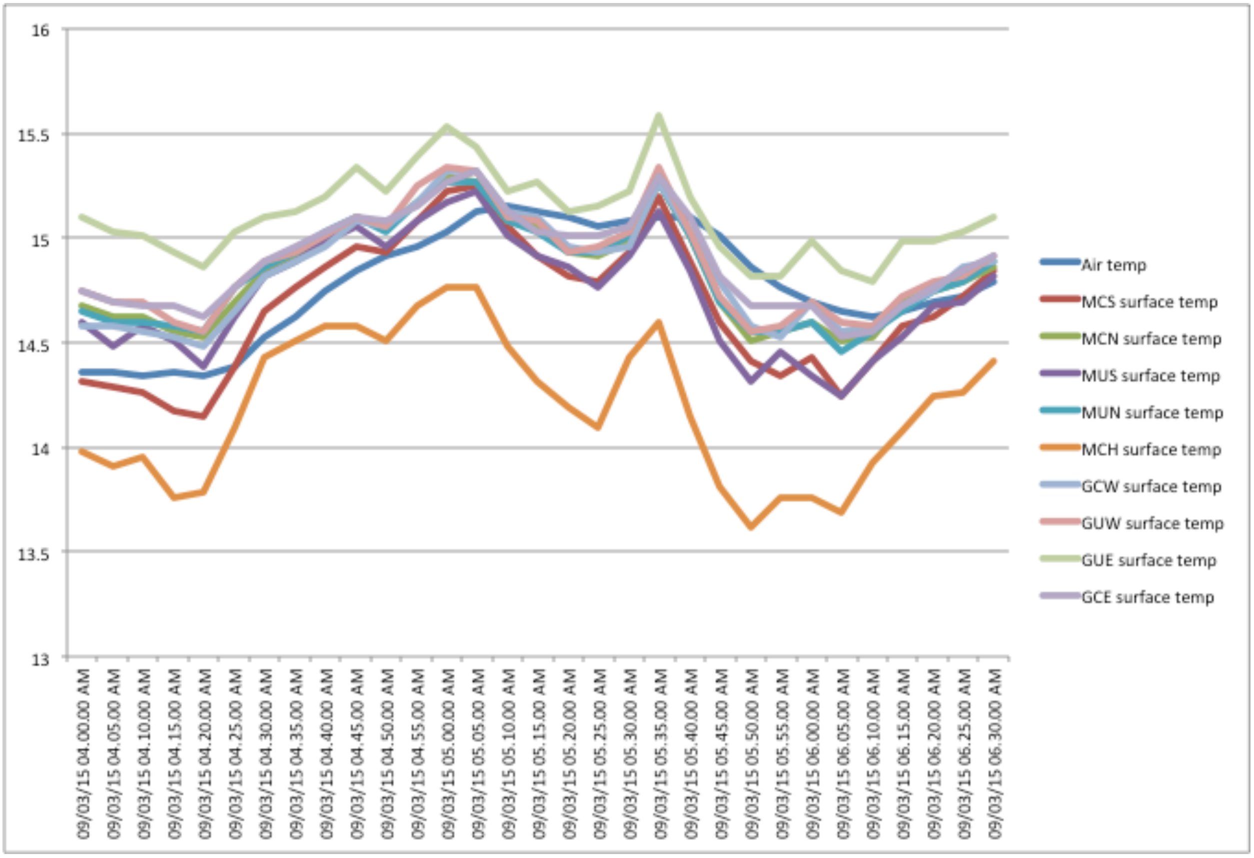

Figure 4 - Experiment 1: Temperature difference between air temperature and surface temperature for the different samples, between 4:00 am and 6:30 am, Sep 3, 2015.

The Metal Coated Horizontal (MCH, in orange in the graph) sample consistently displayed the lowest surface temperature, due to a combination of higher emissivity from the white metal surface, the effect of the titanium dioxide nanocoating, and the horizontal exposure, which promoted a higher view factor to the cold night sky, thus maximizing radiative heat losses from the metal and decreasing its surface temperature.

Figure 5 shows the temperature difference between air temperature and surface temperature of the coated white metal horizontal sample (MCH), which reached up to 1.4 C°, thus helping to promote superficial condensation.

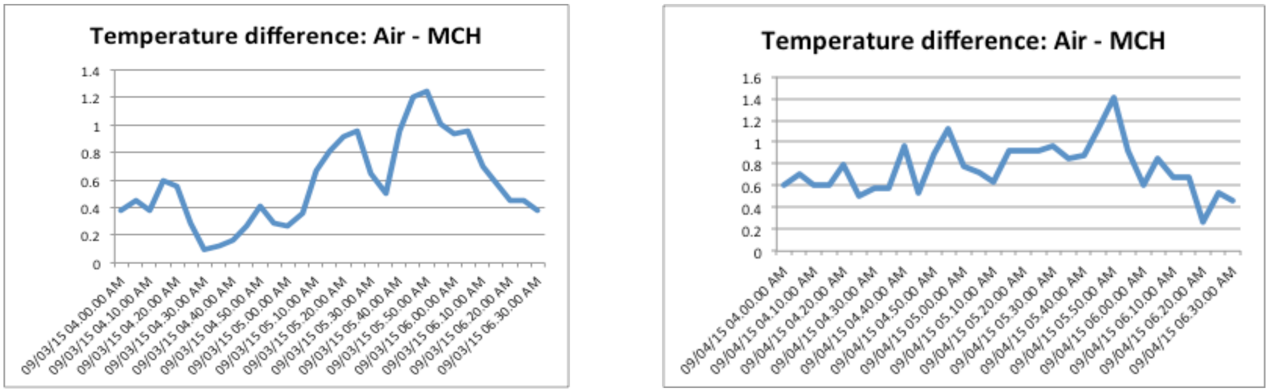

Figure 5. Experiment 1: 2 examples of temperature difference between air temperature and surface temperature of the coated white Metal Coated Horizontal sample (MCH), between 4:00 am and 6:30 am. Left: Sep 3, 2015, temperature difference reached 1.2° Celsius. Right: Sep 4, 2015, temperature difference reached 1.4° Celsius.

Experiment 2 ran from November 26 to December 21, 2015. Six samples were monitored (5 metal + 1 glass). We tested two tilt angles (10° or horizontal), and two orientations, East and West, which were selected according to prevailing wind directions, as measured in previous experiments. Horizontal angles were tested due to expected major radiative cooling during the night (compared to vertical), but the 10º tilt was added to assess the impact of providing some protection against wind, by means of tilting the surface. The legend code for the samples tested is: MUH – Metal Uncoated Horizontal; GCH – Glass Coated Horizontal; MC10FE – Metal Coated, 10° tilt, East facing; MC10FW – Metal Coated, 10° tilt, West facing; MU10FE – Metal Uncoated, 10° tilt, East facing; MU10FW – Metal Uncoated, 10° tilt, West facing.

Figures 6, 7 and 8 display some of experiment 2 results, and values for environmental variable such as air temperature, dew point temperature and relative humidity (RH). The Metal Uncoated Horizontal (MUH) sample is always colder and closer to dew point temperature than the glass coated horizontal sample (GCH), showing that the low emissivity of the material is a major factor at stake, offsetting the effect of the nanocoating applied to the glass. The Metal Uncoated Horizontal (MUH) is always colder and closer to dew point temperature than the metal coated tilted samples, demonstrating that there is no benefit in tilting the samples, as the protection from wind is not significant, and the decrease in the radiative heat loss to the night sky offsets it.

When comparing east facing coated vs. uncoated samples, it is more frequent that the coated surface comes closer to dew point T, while the opposite case is rare, even if it happens. The above applies also to samples facing west. The relation between these occurrences and wind speed and direction where inconclusive. However, since the horizontal sample always had a better performance, continuing this line of analysis was considered not relevant.

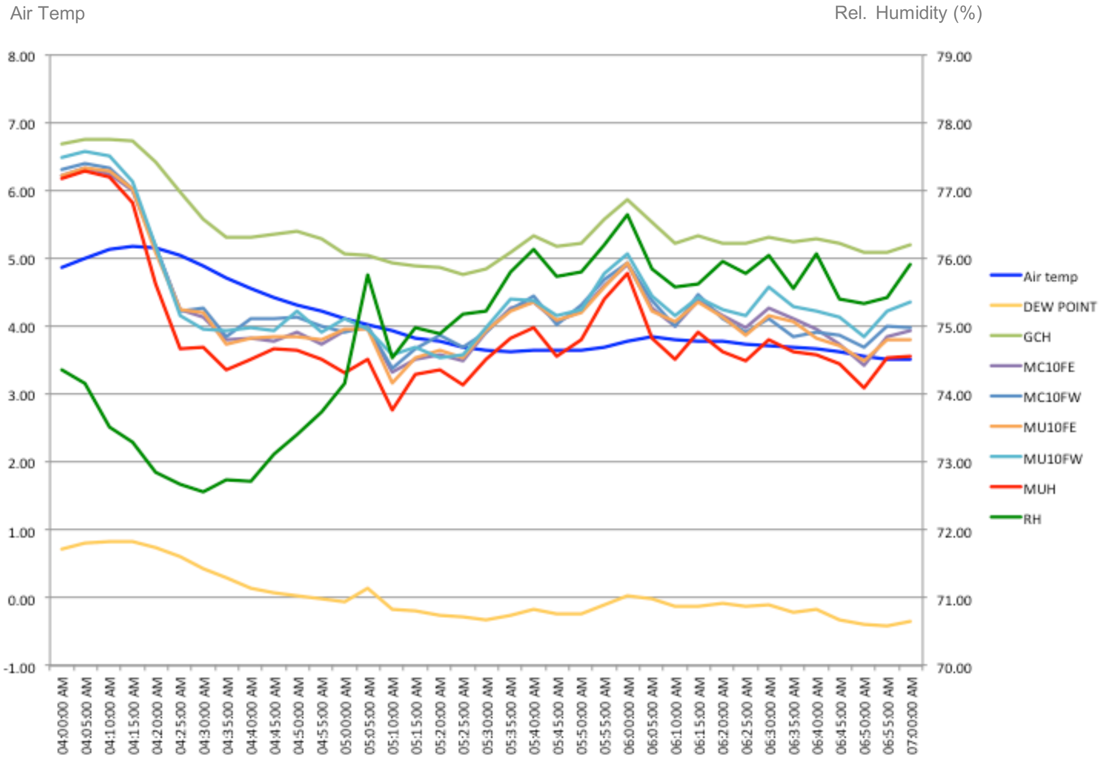

Figure 6 - Experiment 2: Surface temperature for different samples, between 4:00 am and 7:00 am, Nov 29 2015. Environmental variables: Air temperature, relative humidity, dew point temperature.

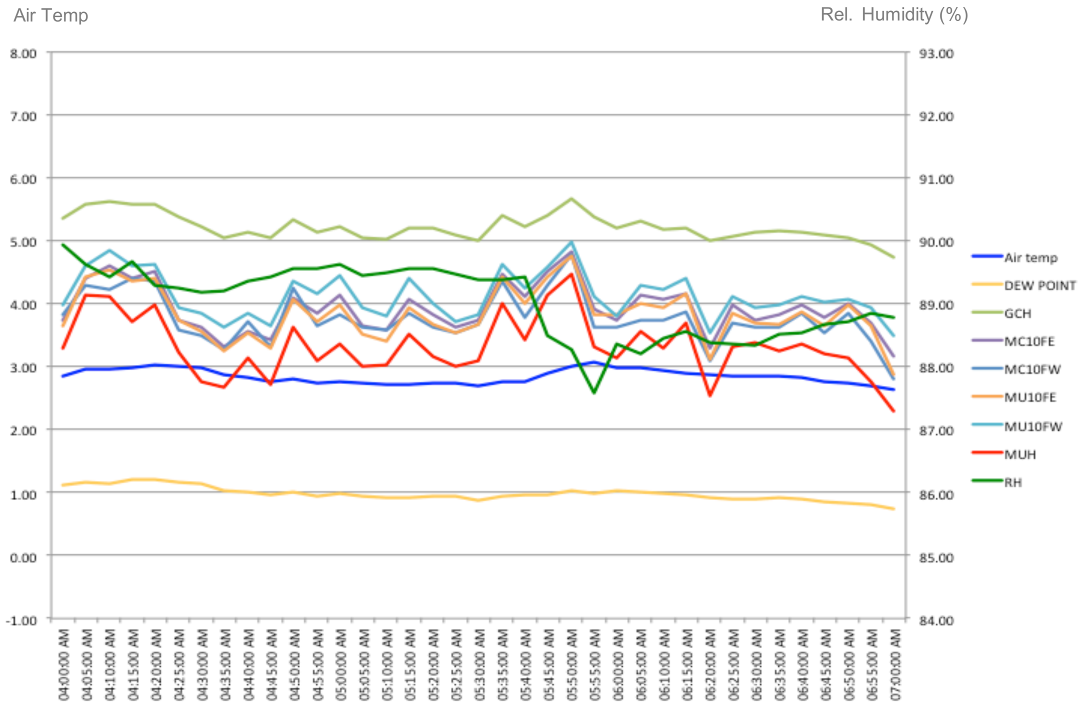

Figure 7 - Experiment 2: Surface temperature for different samples, between 4:00 am and 7:00 am, Dec 14 2015. Environmental variables: Air temperature, relative humidity, dew point temperature.

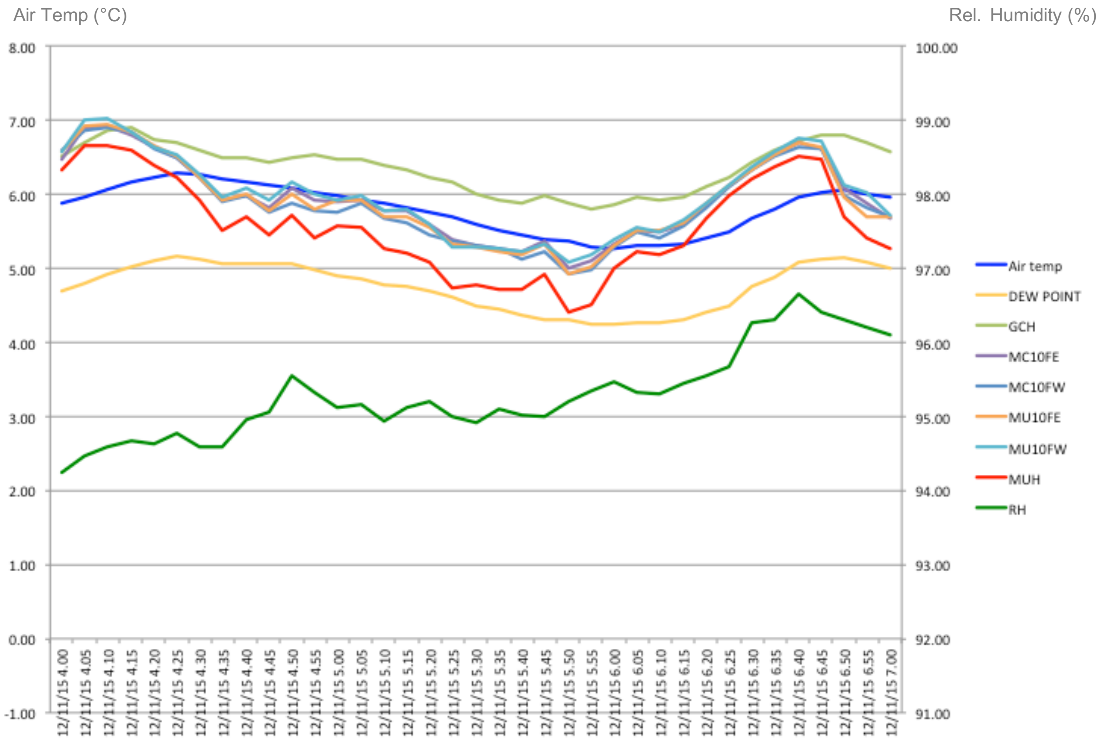

Figure 8 - Experiment 2: Surface temperature for different samples, between 4:00 am and 7:00 am, Dec 11 2015. Environmental variables: Air temperature, relative humidity, dew point temperature.

Experiment 2 allowed to conclude that a high emissivity metal material with a titanium dioxide nanocoating placed horizontally facing the night sky will achieve the lowest surface temperatures.

In terms of building envelope applications, the consistently poorer performance of glass in relation to metal makes potential applications to large glazing facades less interesting, even when self-cleaning titanium dioxide coatings are applied. As for metal clad building surfaces, the fact that horizontal samples consistently achieved lower surface temperatures makes the research more likely to be adequate for roofs than facades. As horizontal white metal seems to offer the most promise, an interesting synergy could exist with the field of cool roofs, a technology used for decreasing heat gain in buildings, and to decrease urban heat island effect. White metal cool roofs could then double their functionality as condensation water collectors, with little increased cost.

3. **Analysis of climate variables**

Despite the fact that the horizontal white metal coated samples reached the lowest surface temperatures, it is possible to see that only rarely they reached surface temperatures low enough to generate condensation (below dew point). The percentage of time that condensation was reached was analyzed for different experiments, for the coldest period of the day (between 4 and 7am). During the measurement period of October 3-13 2015, condensation happened 23% of the time. During the November 26 – December 21 2015 period, condensation happened only 5% of the time. If these calculations were performed for the entire 24 hours period of the day, then the Oct 3-13 period would drop to 3% of the time, and the Nov 26-Dec 21 period would represent only 0.7% of the time. Note that this rough calculation does not account for any rain periods, and already takes into account the lower surface temperature that the high-emissivity coated metal is able to achieve in relation to air temperature, thus making it more likely for condensation to occur. This estimative shows that the periods of the day in which condensation might actually occur will be limited, even though that will vary significantly with local climate conditions.

A more detailed analysis of the combined behavior of air temperature, metal surface temperature and relative humidity provides some insight into why condensation is difficult to promote. Figures 6, 7 and 8 show that surface temperature (red line) roughly follows the profile of air temperature fluctuations (blue line), but is also highly influenced by relative humidity levels (green line). In several cases it is possible to observe that high RH had the effect of cancelling the positive effect of decreasing air temperatures, thus making it difficult for condensation to occur, even during the confluence of high humidity rates and low air temperatures. When air temperature decreases, relative humidity increases. This increase of humidity in the air, however, decreases the radiative heat loss to the night sky, and thus surface temperature of the metal samples becomes sometimes higher than air temperature, in the presence of very high humidity levels. This cancelling effect in the generation of low temperatures, caused by the otherwise desirable increase in relative humidity levels, is an important cause identified for the low occurrence of condensation. It may represent a shortfall of the application of radiative systems in climates where this combination of variables is likely to occur. A more extensive analysis of the climatic characteristics adequate for this type of system is required.

Looking at the average psychrometric conditions of outdoors air during the period of the experiments, it is possible to see that a large amount of water vapor was present in the air. Under the measured temperature and relative humidity conditions, an estimated 63g of water is present in every cubic metre of air. However, the physical phenomena in action were not combined in the adequate manner to create the conditions for extraction of that water vapor from the air, in the form of water. The following section focus on current efforts for finding new, biomimicry-inspired methods to extract water from air, and proposes a new method to address this question.

6. The role of biomimicry and nanotechnology in fog capturing

Some of the ongoing efforts to optimize fog collection processes are based on mimicking nature in different ways (Azad *et al.*, 2015; Zhu, Guo and Liu, 2016). The most efficient harvesting systems known in the planet are found either on plant leaves or on insects, which have developed the ability to survive in environments with very low levels of water availability, exploiting the water content of humid air (Martorell and Ezcurra, 2002; Garrod *et al.*, 2007; Ebner, Miranda and Roth-Nebelsick, 2011). An investigation on the possibilities offered by nanofabrication of surface patterns to enhance the surface yield is presented below. Many different approaches can be used to pursue this objective, such as the creation of nano-textured surfaces characterized by pillars or cones to promote condensation, or the design of specific patterns that can be printed on façade panels during production process to enhance drop accumulation and direction of collected liquid to a particular location featuring larger collection devices (Wang *et al.*, 2015; Zhang *et al.*, 2015). Both these options require further study and laboratory testing, but previous studies have already demonstrated how highly hydrophobic surfaces promote condensation of suspended water droplets (Cheng *et al.*, 2011; Park *et al.*, 2013; Choo, Choi and Lee, 2015).

Other devices for water harvesting from fog are to come on the market in the near future, as their technology is currently under development. This is the case of such nature mimicking systems as the plate-based fog collector, which recalls the feeding mechanisms of shorebirds, who usually collect water droplets on their beaks through repeated opening and closing. Small prototype testing of this technology, based on the use of metal plates to recall the two parts of the shorebird beak, have already given promising results (Heng and Luo, 2014). Other nature-mimicking technologies mimic plant leaves and rely on the presence of tridimensional hierarchical structures for fog harvesting (Andrews *et al.*, 2011).

The phenomenon of water condensation is governed by nucleation (Yu et al. 2012). Humid air must overcome an energy barrier to nucleate, so tuning the chemistry and geometry of a surface is a powerful way to change the surface energy and enhance fog-water conversion. Many attempts have been made to engineer the geometry and chemistry of fog harvesters in order to increase their efficiency. One such notable case is that of the mesh collectors. In 2013, McKinley studied and modeled the condensation of fog on different types of meshes, which led to the optimization of the woven geometry, size of the holes and radius of the wires (Park et al. 2013). Mesh fog harvesters can collect from 1 to 10 liters/m^2 of water per day but their installation is limited to cliffs or hills and requires the presence of wind to function. On the other hand, biological structures demonstrate extraordinary fog collection abilities in a variety of regions with different climatic conditions and do not require moist to be carried by wind (Ju et al 2012a, Parker & Lawrence 2001, Zhai et al. 2006, Heng & Luo 2014, Dong et al. 2012, Hou et al. 2012). The special wetting abilities of such plants and animals result from the unique micro- and nano-scale structural features on their surfaces (Ju et al. 2012b). Nanotechnology can be a powerful means to mimic biological structures, thanks to its nanoscale patterning capabilities.

To understand how nanotechnology can help increasing the efficiency of fog collectors, the condensation of water on patterned surfaces has been thoroughly researched (Yu et al. 2012, Narhe & Beysens 2006, Dorrer & Ruhe 2006, Chen et al. 2007, Boreyko & Chen 2009, Dent et al. 2009). The general conclusion of these studies is that an optimal geometry to promote condensation should have a surface energy gradient, a Laplace pressure differential and many points of nucleation (Hou et al. 2012). In plants like the Opuntia microdasys cactus, the tip of each needle acts like a nucleation point, then trichomes and grooves generate a strong capillary force that drag drops away from nucleation points to achieve a continuous condensation (Ju et al, 2012a). Dong et al. (2012) demonstrated the low-cost microfabrication of a bioinspired knotted fiber that resembles a spider web and exhibits an outstanding water collection potential. Similarly, Andrews et al. (2011) observed how the complex hierarchical microstructure of the Cotula Fallax allows the plant to effectively generate nucleation of small drops over the entirety of the leaf surface in a hydrophobic regime (Cassie−Baxter effect). More recently, Park et al., (2016), developed a design approach based on principles derived from Namib desert beetles, cacti, and pitcher plants that synergistically combines several aspects of condensation. Inspired by the role of the beetle’s bumpy surface geometry in promoting condensation, and using theoretical modeling, it was possible to maximize vapor diffusion flux at the apex of convex millimetric bumps by optimizing their radius of curvature and cross-sectional shape (Park et al., 2016).

The fabrication of similar bio-inspired structures would accelerate the development in the field of fog harvesting and pave the way for its widespread implementation. Though, current processes and techniques in nanotechnology hardly enable the low-cost fabrication of complex, hierarchical, three-dimensional (3D) structures. Recently, nanotechnology has also started exploring fields other than electronics, and capabilities for 3D low-cost patterning are increasingly being researched. Even though more advancements in this area are needed, one of the most viable solutions to manufacture large-scale, inexpensive biomimetic structure for fog capturing seems to be nanoimprint technology (NIL). NIL is a low-cost, high-throughput lithography technique with sub-10 nm patterning resolution that is allowing a variety of new, unconventional applications spanning medicine, biology, photonics and electronics (Ross 2013, Cao et al. 2002, Khusnutdinov et al., Calafiore et al. 2015). In particular, if implemented in a roll-to-roll fashion, NIL can massively produce nano-patterned panels with biomimetic fog capturing features.

Figure 9 briefly describes the fabrication process currently being envisioned for fabrication of a Fog Harvester panel, including mold fabrication by 3D laser lithography, nanoimprinting lithography, resist crosslinking by UV-light, and demolding of the biomimicked structures. The right side of the figure illustrates the Fog Harvester device at work, as fog flows through the artificial barb, nucleates, and water gets dragged to micro-channels for collection on macroscopic pipes.

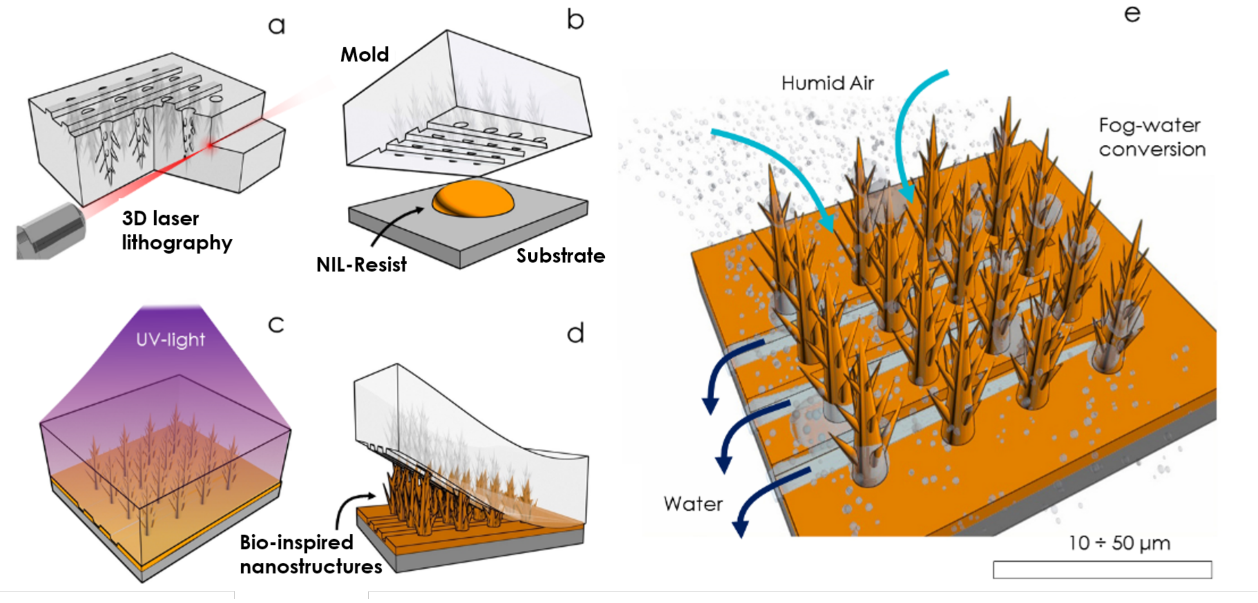

Figure 9. Fog Harvester fabrication process: a) Mold fabrication by 3D laser lithography. b) Nanoimprint lithography step. c) Resist is crosslinked by UV-light. d) Demolding of the biomimicked structures. e) Device at work: fog flows through the artificial barb, nucleates, and gets dragged to micro-channels for collection on macroscopic pipes.

Nano-patterned panels would convert fog into water in a wide variety of environmental conditions and in absence of wind, just like solar panels are employed to harvest electricity from sun radiation. The role of nanotechnology in this field should be further explored, since it can enable the implementation of fog harvesting as an inexpensive, clean source of fresh water, not only in arid climates but also in cooler and more humid climate zones.

7. Conclusions

Based on the literature review of different technologies already available on the market presented in the first part of this work, an investigation of water harvesting from fog in the case of radiative condensers has been performed. In fact, the significant water volumes collected by the galvanized iron roof presented in the first part of the work, even if in particularly favorable climatic conditions, gives confidence to conduct further research for fog harvesting on metal surfaces.

Fog collection potential on radiative condensers has been assessed through a set of experiments using high emissivity white paint, both uncoated and coated with a titanium dioxide nanocoating, and placed either horizontally or tilted towards/against prevailing wind orientations. Surface temperature values were recorded for the coldest period of the day, between 4am and 7am, together with environmental variables such as air temperature, dew point temperature and relative humidity. It was possible to conclude that a high emissivity painted metal material with a titanium dioxide nanocoating placed horizontally facing the night sky will achieve the lowest surface temperatures. In terms of metal clad building surfaces, the fact that horizontal samples consistently achieved lower surface temperatures makes the research more likely to be adequate for roofs than facades. These results are also consistent with the high yield reported in the literature for radiative systems based on metal roofs. As horizontal white metal seems to offer the most promise, an interesting synergy could exist with the field of cool roofs, a technology used for decreasing heat gain in buildings, and to decrease urban heat island effect. White metal cool roofs could then double as condensation water collectors, with little increased cost.

However, an analysis of the combined behavior of air temperature, metal surface temperature and relative humidity provides insight into why condensation was difficult to promote for much of the time the experiment run. In several cases it is possible to observe that high RH had the effect of cancelling the positive effect of decreasing air temperatures, thus making it difficult for condensation to occur, even during the confluence of high humidity rates and low air temperatures. When air temperature decreases, relative humidity increases. This increase of humidity in the air, however, decreases the radiative heat loss to the night sky, and thus surface temperature of the metal samples becomes sometimes higher than air temperature, in the presence of high humidity levels. This cancelling effect caused by the otherwise desirable increase in relative humidity levels, was an important cause identified for the low occurrence of condensation in the sample metal surfaces.

To increase the promotion of condensation in radiative systems, we propose the use of bio-inspired nanocoatings that would accelerate development in the field of fog harvesting and pave the way for its widespread implementation. These nanocoatings would be based on the creation of a nanoscale 3D optimal geometry designed to promote condensation, characterized by a surface energy gradient, a Laplace pressure differential and many points of nucleation. Current processes and techniques in nanotechnology hardly enable the low-cost fabrication of complex, hierarchical, three-dimensional structures, but new advances in capabilities for 3D low-cost patterning are increasingly being researched. The most viable solution to manufacture large-scale, inexpensive biomimetic structure for fog capturing seems to be nanoimprint technology (NIL). NIL is a low-cost, high-throughput lithography technique with sub-10 nm patterning resolution that, if implemented in a roll-to-roll fashion, can massively produce nano-patterned metal panels with biomimetic fog capturing features. These nano-patterned panels would convert fog into water in a wide variety of environmental conditions and in absence of wind. The role of nanotechnology in this field should be further explored, since it can enable the implementation of fog harvesting as an inexpensive, clean source of fresh water, not only in arid climates but also in cooler and more humid climate zones.

Acknowledgements

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