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Innovation and Evolution of Forms and Materials for Maximising Dew Collection

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Abstract - A year long study focusing on maximising dew collection using new and novel forms and materials commenced with a literature review and then the testing of nearly two hundred materials and forms using a dew simulation chamber. The research asserts that whereas present and past dew collection studies have focused on passive slippery, hydrophobic, inclined planar forms, that there are other forms that show potential for collecting dew. These include hydroscopic metallic and carbon foams with large interstices where dew can collect but which are also slippery and hydrophobic so that the dew can be rejected by gravity and then replaced by more dew. These types of forms could be used in semi-passive systems where people are at hand to extract the dew. Biomimesis, particularly with regards to cacti is investigated and materials with spiny / lanceolate projections show positive results as do some open foam materials. Other forms / materials derived from nature which are investigated and which require further study include airfoil shaped forms derived from beetles, corrugated and ribbed/finned shaped forms derived from leaves, particularly cacti, as well as insects. The study also investigates high emissivity materials. The testing of the forms and materials in the dew chamber provides a means for comparing their ability to collect dew. However as the dew simulation chamber is not a device specifically designed for dew research the results cannot be used definitively to predict the amounts that could be collected out doors. The research, however presents a number of potential new paths for maximising dew collection which should be taken further and tested in the field.

Keywords *– dew; dew collection; dew collection forms, dew collection materials, biomemisis and dew collection, dew simulation chamber; airfoil shapes*

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Introduction

There is great need to find alternative water sources in hot, dry arid areas. One potential way of providing supplementary water is through the collection of dew. The idea of collecting as much dew as possible and how one could do this effectively was the main aim of a 1 year study.

In order to maximise dew collection three things are required. Firstly, maximising surface area. Secondly, finding the most effective materials that could attract dew and finally once the dew had settled, there needs to be effective methods of delivering and collecting this water. With the right atmospheric conditions, this is readily done; on clear nights, with little or no wind movement, when dew point is reached, dew will form on glass or other slippery materials such as PTFE (Teflon®) and slip downwards by gravity to a conduit / collecting chamber. Under the right conditions this may be enough for a plant to be watered and survive, but one would require huge planar surfaces to provide enough water for numerous animals and/or people.

The problem was that previous approaches to non-mechanical dew collection were mostly centred on 1) the quantities of dew that could be collected and 2) the quality of this dew and whether it was fit for human consumption. Most of this research undertaken in the Mediterranean and Israel typically used flat, angled planar surfaces with a rather narrow variety of materials and it was this lack of variety in the research that encouraged this research into other novel types of forms and a different range of materials. The use of flat, angled planar surfaces, is all well and good, and it should be possible to collect considerable amounts of dew, but this would require considerable land, space and materials.

Most research and sources Monteith (1957), Sharan, Beysens et al (2007), Jacobs et al (2008 [after Monteith 1957]) suggest that dew is collectable and that that the maximum amount of dew that potentially could be collected ranges between 0.8 l/m^2/day to 1 l/m^2/day. [i] In e-mail correspondence to the author, [ii], Sharan notes that the maximum dew they received in Kothara, India was in April at 0.71 litres/m^2 per night. And dew fell here for 103 nights. This is a considerable amount of water as 0.71 litres/m^2 per night for 103 days equates to 73.1 l/m^2 per annum. Thus a surface of 10 m^2 would be able to collect 720 litres per annum. This is approximately the amount of water for 1 person drinking 2 litres per day per annum [iii].

Innovation and Evolution of Forms and Materials

One of the main problems in dew research is the logistics of setting up apparatus in the field in relatively remote areas and the length of time this takes to get results and thus alternative methods for collecting dew were devised. As far as it is known, for the first time a dew simulation chamber was used to compare dew formation and discharge from a variety of man-made materials and forms [iv]. Forms and materials were chosen and/or made following the literature review on dew collection and as part of the iterative learning process as the research progressed. The dew collection forms were either constructed by the author or bought as proprietary products that are used for other purposes. The physical character of these forms on the whole have their origin in nature (but are man-made) and centre on shapes which tend to: 1) increase surface area 2) theoretically to act as radiators and thus remove heat more rapidly than solid forms and 3) theoretically alter air movement. Forms thus used echo the spines and fins of cacti and the airfoil wings and body shapes of insects and man-made wings.

Additionally, whereas in the past, dew collection has focused on hydrophobic materials that had little or no porosity and were single sided, there are more options to collect dew than this single passive method. Rather, there are three main possibilities for passive and semi-passive [v] type dew collection as far as the types of materials are concerned:

1. Hydrophobic materials: Includes materials such as glass, steel, plastics that are relatively smooth and without large pores. These materials may be used in totally passive systems where dew runoff occurs through gravity without human intervention and then it is collected/stored/treated and used. The efficacy of these smooth materials can be increased through the application of slippery coatings such as PTFE (polytetrafluoroethylene) registered as Teflon®. These systems have the potential to be used in situ, to target collected dew directly to plants, into animal drinking troughs and into collection tanks for use by people.

2. Hydrophilic materials: The use of large pored materials where dew forms by adsorption[vi] within the pores. It is apparent from a review of the literature that this type of system has not yet been investigated. The use of this system is not totally passive. Water would be collected for example within a sponge type material and then released by squashing or squeezing the water out, or by centrifugal force after it has collected within the sponge. This system needs human intervention at the end stage.

3. Combining hydrophilic and hydrophobic materials: This type of system would for example take materials such as a sponge and coat the sponge material with a hydrophobic coating such as PTFE. These types of materials also include coated metal foams, metal sponges, porous metals, cellular metals, sintered metals and ceramic foams. The water would also have to be released by man by for example by expelling the water by centrifuge.

Single Side versus Double Side Collectors

In reforestation research using tree shelters [vii] to collect dew del Campo et al (2006) noted that the single wall design was more effective than the double wall shelters. Furthermore they assessed that condensation conditions with lower temperatures were recorded within the shelters and condensation time per day recorded for the single wall tree shelter was longer compared to twin-walled tree shelter. Del Campo et al thus suggest that tree shelters may act as radiative condensers due to their high surface/mass ratio and the low wind velocity inside them. These facts are important as it is well known that dew forms on surfaces due to radiative cooling, i.e. terrestrial radiation being given up to the sky in conjunction to minimal air movement. Del Campo et al note that the twin walled shelter was less effective in facilitating condensation due to the fact that the inner face of the single walled shelter had 40% more available surface area to collect dew. (Figure 1) Although the twin walled shelter had a greater area overall, (taking the inner surfaces into account as well), the capillary action of water within the micro-tubes did not allow the free run-off of coalesced water. They suggest that a 10 mm^2 micro tube would potentially overcome this. Del Campo et al furthermore note that in their research that the outside walls of the tree shelters were irrelevant and that this had to do with the movement of air, which prohibited dew collection. A number of lessons can thus be learnt from this research:

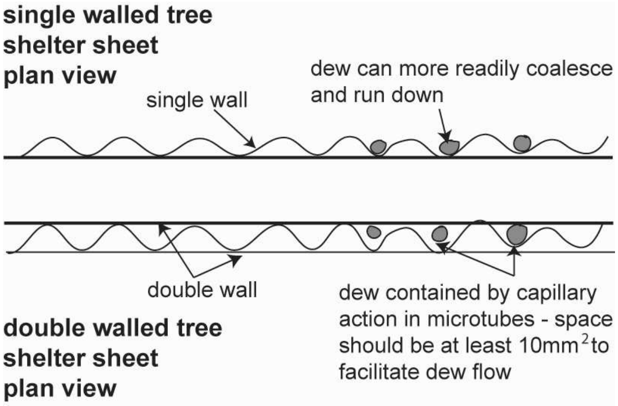


Figure 1. Dew flow is hindered if there is not enough space and capillary action is too great

1. Dew could be collected from both sides of a form, as long as cooling occurred on both surfaces;

2. If a double skin is used, increasing the surface area for dew collection is not enough. The surfaces must be far enough apart to limit stasis of water run-off through capillary action and surface water tension. The space between surfaces should potentially be at least 3 mm apart taking the suggestion by Campo et al that a 10 mm^2 micro-tube would be advantageous.

3. Increasing the surface area for dew collection must go hand-in-hand with creating hydrophobic slippery

surfaces where the dew can readily be flushed and replaced.

4. Whereas in the past most dew collectors have been orientated at an angle off the horizontal, the research indicates that radiative cooling to the sky may be effective with surfaces orientated vertically. Beysens et al. (2003) notes that radiative cooling is most efficient when the ø (variable angle) is 0 degrees, i.e. horizontal, but this is complicated by wind, and the optimum angle in their study was 30º from the horizontal. However, they do note that with regard to releasing water that the optimum and most effective gravitation pull is where ø = 90. However, an angle of 30º provides a good compromise as at this angle, the gravity force acting on the drops is still 50% of the maximum available force, obtained and the cooling gain remains in the order of 120% (Beysens et al., 2003).

5. Having vertical and enclosed structures may encourage dew formation by creating still air within the structure where on the outside horizontal and for that matter vertical surfaces would not collect dew because of air movement. (This is disputed below, as some air movement could help to facilitate dew through cooling.)

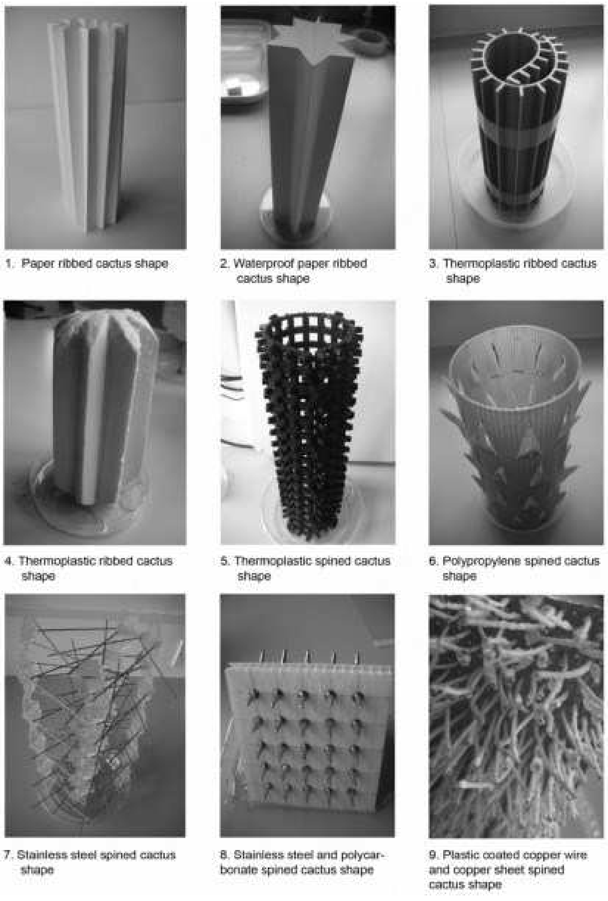

1. Paper ribbed cactus shape
2. Waterproof paper ribbed cactus shape
3. Thermoplastic ribbed cactus shape
4. Thermoplastic ribbed cactus shape
5. Thermoplastic spined cactus shape
6. Polypropylene spined cactus shape
7. Stainless steel spined cactus shape
8. Stainless steel and polycarbonate spined cactus shape
9. Plastic coated copper wire and copper sheet spined cactus shape

Figure 2. A variety of biomimetic forms and various materials tested in the dew simulation chamber.

6. The internal face of the tree shelters used by Del Campo et al. is corrugated. It is suggested here that, these corrugations do more than just increase the surface area for dew to collect but also that these corrugations may act as micro-radiators and that corrugations may by their very form alter the microclimatic conditions facilitating dew formation. (Refer to the section below on Corrugation.)

Most dew research has utilized the upward radiating face of the dew collector. Dew formation on the inner side of the tree shelters suggests that in the right conditions both sides of the object collector could potentially amass dew, thus increasing the potential for the amounts collected (Figure 2, Photo 6).

Dew Formation and Air Movement

It is apparent as noted above, that the movement of air in and around a body or object affects condensation and dew formation. Sharan et al. (2007) note that in response to their research in Kothara, India that high windspeed increases the heat exchange by convection and turbulence and prevents dew from forming. Most dew in this case formed with a wind speed of approximately 1 m/s but less than 4 m/s. Beysens et al. (2006) agree that winds of about 1 m/s are favourable for replenishing humid air around a condenser. However, Beysens et al (2007) note that on island sites dew has been collected at wind speeds up to 6 m/s.

The biomorphic qualities of slipperiness and hydrophobia have been used in dew research with little exploration with regard to associated air movement. Until now the shape and form of most dew collectors remains mainly associated with single surface flat planes. But the natural world tells us something else and the collection of water through moving air across a body is exploited by some plants as well as animals. The *Onymacris bicolor* (Figure 3), and *O. unguicularis* beetles of the tenebrionid beetle family collect water by fog-basking (Hamilton and Seely, 1976).

Figure 3. Fog basking tenebreonid Namibian beetle. Photo courtesy and copyright of Jochen Bihn

These Namibian diurnal species climb up onto cool fog-swept dune crests at night and assume a head down stance to allow fog to deposit onto their carapaces (Henschel and Seely, 2008). Drops of condensed water run down towards the mouth and the beetles drink, gaining an average of 12% of body weight (Henschel and Seely, 2008). As noted by Henschel and Seely (2008) the alignment of the beetles carapace towards the fog and its heads down inclination is effective in directing water to the mouth of the creature. The collection of water is furthermore enhanced through the wax coating that is secreted by many tenebrionids [viii]. This coating not only reflects some of the suns radiation and protects the beetles from water loss, abrasion and microorganisms but also makes the exoskeleton slippery, facilitating water run-off (Sandro et al.).

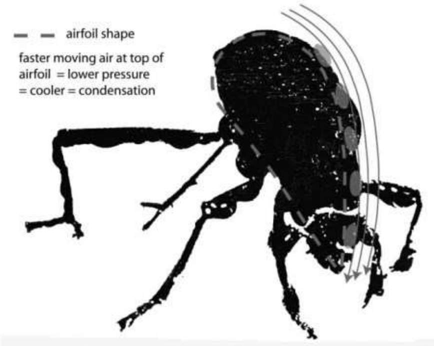
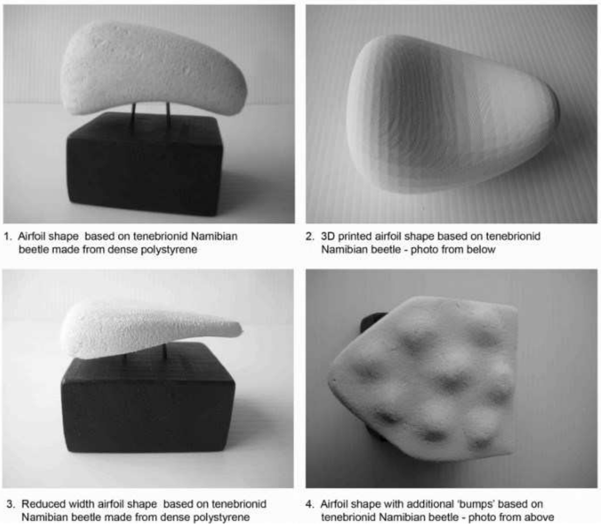


Figure 4. Beetle carapace is airfoil shaped and may enhance water collection

Cohen and Rubner at MIT have investigated the bumps of the beetles and have created super hydrophobic materials to aid dew collection (Trafton, 2006). However, the behaviour and the hydrophobic coating of the beetles may not be the only factors contributing to condensation. It is suggested here that perhaps the airfoil shape of the beetles body (Figure 4 and Figure 5), contributes to water condensation in a similar way to the way that condensation collects and is directed along an aeroplanes wings.



1. Airfoil shape based on tenebrionid Namibian beetle made from dense polystyrene
2. 3D printed airfoil shape based on tenebrionid Namibian beetle - photo from below
3. Reduced width airfoil shape based on tenebrionid Namibian beetle made from dense polystyrene
4. Airfoil shape with additional 'bumps' based on tenebrionid Namibian beetle - photo from above

Figure 5. Various airfoil shapes based on tenebreonid beetles and tested in dew simulation chamber

This phenomenon occurs in flight because of the conditions brought about by the shape of the airfoil in relation to moving air. However, what is not known is whether the effect occurs at low speeds as suggested by the shape of the beetles' bodies. It is thus suggested that airfoil shapes could assist in increasing condensation and dew capture because of the process described as follows:

1. Slow moving wind passes over airfoil shape.

2. Air above the airfoil speeds up and air pressure becomes slightly lower. A lower air pressure equates with more moisture in the air as water molecules are lighter than nitrogen molecules, which constitute 78% of the molecules in air (Ahrens, 2007). Slightly cooler temperatures occur with the increase in moisture and thus condensation occurs. Conversely, air below the airfoil is slower moving and air pressure becomes higher helping to create lift. A higher air pressure equates with less moisture in the air as air without moisture is heavier than air with moisture as water molecules are lighter than the nitrogen molecules (Ahrens, 2007).

3. Condensation thus occurs on the convex upper surface, which then flows by the pull of gravity to the trailing edge of the airfoil before dripping off.

Inspired by these concepts various airfoil forms were constructed and tested in the dew chamber (Figure 5).

Nature also tells us that multiple surfaces as well as smaller surfaces may be more effective in collecting dew. For example, the myriad of needles of *Tamarix* species and for example *Retama raetem* in the Negev desert collect dew and drop the dew towards the roots located immediately below onto the surface of the ground (Figure 6). Similarly although many cactus spines angle upwards and direct dew water to stomata and to the cactus base some cactus species whose spines are oriented downwards direct dew to shallow roots around the cactus.

Figure 6. Condensation on lanceolate leafs and spines can enhance drip to plant roots

Corrugation

It is extremely interesting to note that corrugations could play an important part in dew collection. It is obvious that if dew is forming then one way to collect more of it is to increase and maximise the surface area on which it falls. We have noted above that the single walled tree shelter was a better condensation collector as it had 40% more available surface area to collect dew due to its corrugations on one side (Figure 1). Furthermore, the airfoil body of the tenebrionid beetle is covered with corrugations/bumps, which increase the surface area of the beetle (Figures 3 and 5). The increase in surface area by corrugation is dependent on the ratio between the wavelength and the amplitude (Figure 7).

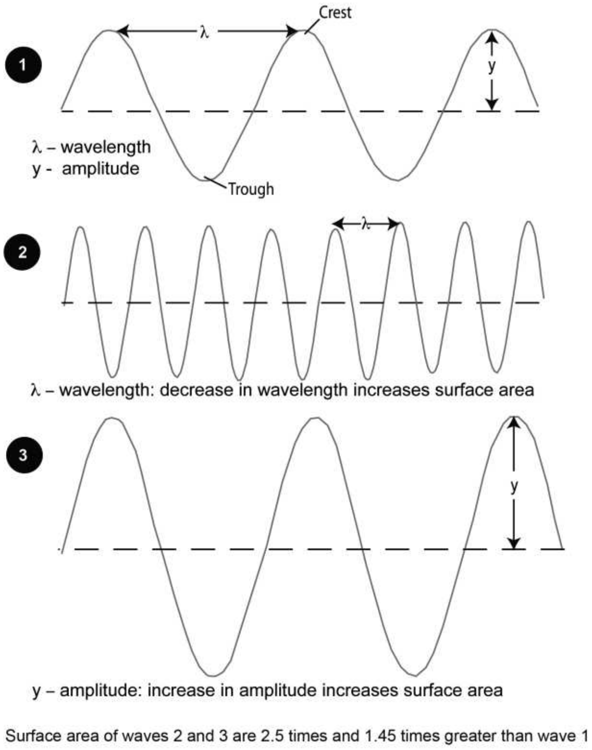


Figure 7. Increases in wavelength and amplitude increase surface area

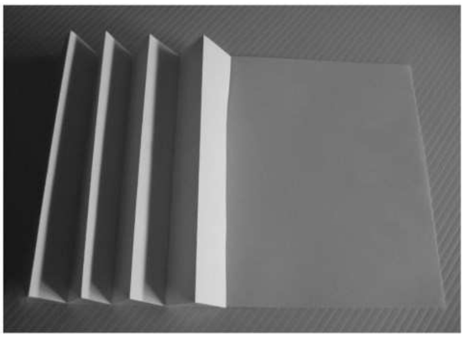


Figure 8. Corrugated forms use vertical space to create more surface area than only using horizontal space

A decrease in wavelength increases the amount of surface area within a given area, whilst an increase in amplitude will similarly provide a greater surface area. Figure 7 illustrates an A4 sheet of paper that has been corrugated and then placed on top of a flat piece of A4 paper. The corrugated piece of paper is contained in approximately half the area of the flat piece of paper and thus by using vertical space, the corrugated profiled paper is 100% more efficient in using the horizontal area as compared to the flat profile.

Many plant leaves are corrugated. De Focatiis and Guest (2002) conclude that leaves may be modelled as thin membranes or laminae with *reinforcements in the form of veins and midribs.* It is the combination of these elements, which provide the flexibility as well as the rigidity required for the leaf to perform its functions and to sustain its own weight and withstand small loads. Leaves such as hornbeam (*Carpinus betulis*) and beech (*Fagus sylvatica*) are completely corrugated (Figure 7). As noted above corrugations add stability but they also add additional leaf surface with increased stomata which can increase photosynthesis and breathing for each individual leaf as well as the whole tree itself. It is quite possible then that in woodlands where there is competition for sunlight the species with leaves with increased surface area has an advantage over other species, which have leaves that are not corrugated.

Figure 9. Beech (*Fagus sylvatica*) leaf with corrugated leaf surface

It is also interesting to note that some insect wings are corrugated. Numerous studies have shown that the highly corrugated wings of the dragonfly (*Aeschna cyanea*) provide extra lift compared to non-corrugated insect wings (Won Kap et al., 2009). Research at The George Washington University show that the pleats give the wings much greater lift than expected in gliding flight and they match or sometimes better similarly sized streamline wings. This is because the air *circulates in the cavities between pleats, creating areas of very low drag that aid the lift-generating airflow across the wing.* (NewScientist.com) As discussed above in the discussion on airfoils, the change in airflow across the top of the wing helps to speed up the air and thus the air pressure becomes lower and a lower air pressure equates with more moisture in the air and consequently cooler temperatures occur with an increase in moisture and thus condensation occurs. It is suggested that this could occur with corrugated forms [ix]. Furthermore corrugations increase surface area, which consequently increases radiative cooling which then also improves the chances for condensation to occur. It is also interesting to note that many cacti have types of corrugated forms and these forms and their potential for dew collection are discussed next.

Biomimesis - Learning from Cacti

Gibson and Nobel, (1990), note that phyllotaxy (leaf arrangement or leaf position), in cacti and most land plants is helically alternate. This is the case for most dicotyledons. The angle that leaves are sequentially produced around the growing stem is in the order of 137.5°. This angle is called the Fibonacci angle [x] and it is the angle that is formed between the growth of cacti primordium as each new one emerges from the apex of the cactus (Gibson and Nobel, 1990). The relevance of the Fibonacci sequence and angle in general plant morphology and with some cacti relates to allowing the leaves and ribs to radiate around the stem or body of the plant to gain as much solar and terrestrial radiation as possible. The opening up of the rib faces of the cactus such as *Ferocactus* species not only allows for more radiation during the day but it is suggested here that the arrangement should also precipitate greater cooling of the cactus surface at night through:

1. An increase in the surface area of the cactus. This results in more stomata for transpiration and therefore greater cooling and potentially this increases dew settlement; and

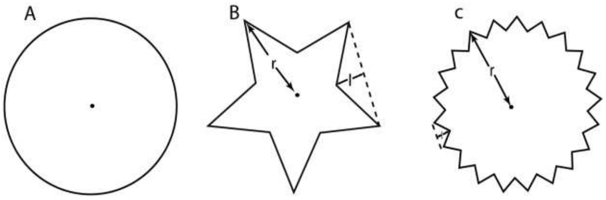
2. A greater flow of air around most of the plant, as compared to vertical ribbed cacti, which should also enhance cooling and thus the settlement of dew.

With regard to the two points mentioned immediately above, the following should be noted:

Gibson and Nobel (1990) state that heat convection is proportional to the difference in temperature between the stem surface and the moving of air just across the air boundary layer next to the surface and that the coefficient of proportionality, which is known as the heat convection coefficient varies with position on the (cactuses) rib. Heat convection is highest at the rib crest as the air movement is greatest at the rib crest, 24% lower at the midrib and 70% lower in the trough where air movement is considerably less (Gibson and Nobel, 1990). They furthermore note that a cactus without ribs should lose heat more efficiently at night because of the more consistent overall airflow. However, this is not necessarily the case as Gibson and Nobel also note that the addition of ribs increase surface area and this allows for greater transpiration and thus cooling.

An increase in surface area through ribs, appears to be marginally beneficial with regards to the growth of succulents. [xi] [xii]. Gibson and Nobel (1990) note that eliminating the ribs on a 21 ribbed plant with a fractional rib depth of 0.15 decreases the surface area by 26%, which would create a similar decrease in transpiration and *hence transpiration cooling* (Figure 8). However, although the effect is considered rather small by Gibson and Nobel (1990), even a small reduction in temperature on a cacti's surface could well activate dew settlement.

It is likely that radiation to the sky at the rib crests is also similar to the heat convection scenario, (illustration 1 below), where it is higher at the rib crest due to increased air movement and lower at the midrib and lowest in the trough.



Cross sections of idealised cactus stems with various rib numbers and depths.
(B) Stem with 5 ribs of fractional rib depth of 0.35
(C) Stem with 21 ribs of fractional rib depth of 0.15. = 26% increase in surface area compared to non ribbed circular form A.
Fractional rib depth equals l/r.

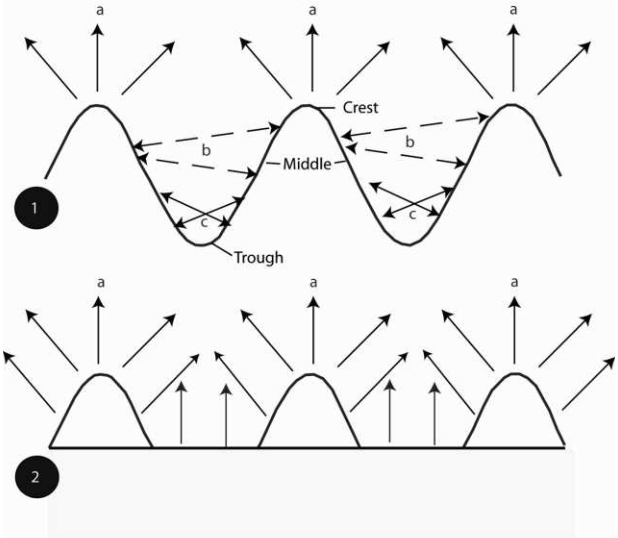
Figure 10. Cacti ribs increase surface area, increase radiation absorption as well as cooling and air movement modification

This is because the rib crests have increased potential to release terrestrial radiation, whilst other areas are releasing as well as absorbing terrestrial radiation being emitted from adjacent surfaces (Figure 9, illustration 1).

Thus it is apparent that ribbed surfaces have the advantage of facilitating convective cooling, radiative cooling as well as increasing surface area, which are useful characteristics when maximising dew collection. However, what is not yet identified is if 21 ribs with a fractional depth of 0.15 increases surface are by 26%, what is the optimum arrangement in terms of number of ribs and rib depth a) to maximise surface area, and b) to maximise the transfer of infrared radiation and/or heat by convection? As noted above Gibson and Nobel state that heat transfer is optimal at the rib crest and 70% lower in the trough and this suggests that increasing crests should improve the transfer of energy and thus better facilitate dew collection.

However, increasing the crests, also means increasing the troughs and this could counterbalance the potential benefits gained with the increase in crests. Increasing the surface area by decreasing the wavelength or increasing the amplitude or both may increase surface area but may also create forms with diminishing returns in terms of energy loss (Figure 7), particularly in relation to radiation loss. It is suggested that a balance needs to be found, which then increases the number of crests, reduces the number of troughs and which also distances each crest away from each other so that they are not affected by terrestrial radiation from adjacent surfaces (Figure 11 illustration 2).

The investigation above inspired various cactus and plant like forms that were constructed or acquired and tested in the dew chamber (Figure 2). Other biomimetic forms that were tested included monofilament nylon mono filament that mimic spider web thread which are often most noticeable in nature when beset with dew drops.



1. Deep troughs in 'radiator' limits loss of terrestrial radiation to the sky due to radiation interaction between middle and trough surfaces (b) and (c)
2. Removing troughs reduces interaction between surfaces and thus increases terrestrial radiation to the sky

Figure 11. Increasing numbers of ribs increase surface area and radiation/cooling

Increasing Surface Area and Angles of Reception in Dew Collection

As noted above, cacti and many other vegetative and faunal forms increase their surface area relative to the space they occupy for a number of physiological reasons. With dew collectors, however, the amount of dew that can potentially be collected is in proportion to the area that is open to radiation cooling. Jacobs et al. (2008) note that an inverted pyramid collector set up at 30° in the Netherlands was able to collect approximately 20% more dew than an inclined planar collector at 30°. Kidron's research in the Negev shows that the angle of repose of collectors is an important factor. He notes the following percentages of dew fall on angled receptors as follows: at 30° (99.8%), at 45° (78.2%), at 60° (42%), at 75° (33.8%), and at 90° (25.6%) (Kidron, 2005). The experiments on various dew forms and materials in the dew simulation chamber reinforces the model that the amount of dew that can potentially be collected does directly relate to the area that is open to radiation cooling. In these experiments dewfall was mainly located on the tops of the forms, which were open to radiative cooling. Other areas on the forms, which were blocked or had less of a straight line path for radiative cooling, collected less or no dew.

Radiative Cooling and Emissivity

In order for dew to form on materials, the material and its surface and the immediate layer of air above it must lose heat. As noted above, this thermal cooling is achieved in cacti and other plants through heat convection and transpirational cooling but the main process of heat loss is achieved through the radiative cooling of objects to the night sky of terrestrial radiation of long-wave infrared energy. [xiii] Earlier in the day these objects would have received short wave light and infrared radiation from the sun and would also have absorbed long wave infrared energy from, surrounding objects and clouds. All objects absorb, reflect and transmit radiation in various degrees depending on the material qualities of the object and the radiative qualities of most materials have been quantified relative to a theoretical black body state, which has a theoretical emissivity value of 1.0. All known man-made and natural materials thus have emissivity values that are < 1.0, where high emissivity materials, i.e. those that are efficient radiators of infrared energy have values approaching 0.99. It appears logical that those materials that have high radiative qualities (i.e. high emissivity values) would be best at absorbing infrared radiation as well as concomitantly releasing it back to the atmosphere under the right conditions. It thus follows that high emissivity value materials are likely to be those materials that are best for collecting dew. Nilsson et al (1994) note that pigmented foils can be used to condense dew and these should combine a high solar reflectance and a high infrared emittance, in order to promote condensation by the radiative cooling effect. They observe that titanium dioxide is a fairly good infrared emitter, but the emittance can be improved by using a mixture of TiO_2 and $BaSO_4$ pigments or only employing a composite SiO_2/TiO_2 Field tests with a 390 micrometers thick polyethylene foil with TiO_2 and $BaSO_4$ pigments gave encouraging results [xiv]. A group of researchers including Nilsson carried out further research in Ajaccio, Corsica. Muselli et al. (2002) set up a $30m^2$ TiO_2 and $BaSO_4$ coated polyethylene foil, which collected on average 3.6 litres of dew on the nights that dew fell, with a maximum of 11.4 litres. This equates to and average of 120 ml/m^2 and a maximum of 380 ml/m^2 respectively per night.

As noted above, emissivity is measured against a theoretical black body (100% emissivity) at a figure of 1.0. Thus the emissivity values of all real materials are calculated as being < 1.0. When regarding condensation on windows in regions with middle and northern European climates, Glaser notes that outside condensation on glass can be counteracted by outside coatings having thermal emissivity values $\epsilon \leq 0.10$, suppressing this heat emission to a large extent and that the frequency of dew formation can be considerably reduced. This is because most types of glass have high emissivity values and this is readily noticed on car windscreens and windows on nights when dew falls. Walton (2009) notes that lighter coloured objects (white, shiny metal) have a low emissivity and emit and absorb little radiation. This may be true for most lighter coloured materials but is in contradiction to TiO_2 and $BaSO_4$ as noted by Nilsson et al. (1994) and Muselli et al. (2002). TiO_2 and $BaSO_4$ are pure white in colour.

It is the case, however, that all of the objects susceptible to cooling also tend to receive higher amounts of dew, condensation, and frost. The formation of dew is then partially dependent on the emissivity value of the material, but the amount of dew collected relates directly to the hydrophobic quality of the material. Rough concrete has a high emissivity value (0.94), but due to its hygroscopic nature it would not be able to release any dew that forms on it. In other words, once the dew is formed it also needs to move away to allow more condensation to occur in the same location. The following list in Table 1 notes a number of high emissivity materials that are generally considered hydrophobic and that could be made more hydrophobic with the addition for slippery surfaces such as PTFE and other coatings.

Table 1. List of some high emissivity materials [1] that are also hydrophobic and that may be suitable for dew collection

Surface Material	Emissivity Coefficient (ε)
Glass, pyrex	0.85 - 0.95
Porcelain, glazed	0.92
Glass smooth	0.92 - 0.94
Oil paints, all colours	0.92 - 0.96
Black Silicone Paint	0.93
Paper	0.93
Paint: TiO2, white	0.94
Black Parson Optical	0.95
Marble White	0.95
Plastics black	0.95
Rubber	0.95
Glass frosted	0.96
Lampblack paint	0.96
Lacquer: dull black	0.97
Plaster	0.98
Polypropylene	0.97
Tape: electrical, insulating, black	0.97
Tile	0.97
Paint: DuPont Duco #71 wrought iron black	0.98
Water	0.98

The emissivity values of materials is not easily predictable and often goes against preconceived ideas and intuition as noted with TiO_2 and $BaSO_4$. Water for example has a very high emissivity value of 0.98 and white marble a value of 0.95. Proof of this is noted by Camuffo and Giorio (2002), in their research on dewfall on monuments. They note that 200 ml can accumulate on horizontal white and green Carrara marble although formation on vertical surfaces was negligible.

Conclusions

A number of interesting possibilities for maximising dew collection have emerged from the literature review and subsequent exploration of ideas as well as from the actual testing of the forms and materials in the dew simulation chamber. The first significant concept to emerge is that dew collection need not rely solely on passive systems and only the use of hydrophobic materials, which is predominantly the case at present. In situations where people are not at hand, passive hydrophobic systems, which drain off dew from slippery collecting surfaces into storage containers or directly to where it is required makes sense. However, where people are present, there is the potential to collect dew using hydrophilic materials, where for example dew forms by adsorption within the pores of large pored materials such as metal and carbon foam. Dew forming on this type of material can potentially also be better released by coating the foam type structures with hydrophobic coatings thus allowing dew to runoff and be replaced by more dew. But if people are present there is no reason why they should not participate in the dew collection process. This concept constitutes a sea-change in the ideas of dew collection. People could intervene, for example, by shaking or spinning the form, to release the dew. Of course such actions could also be controlled robotically by machines but this is unlikely to be feasible in arid regions where many people have meagre resources.

It is clear that one of the main ways to maximise dew formation and collection is to increase the surface area of the collector. In most instances dew collection is conceived using large inclined planar surfaces. This investigation suggests that this can be achieved in various ways, not yet considered in previous research or in the literature, and that the single, flat, planar profile most commonly used is but one way of collecting dew. Investigations of plant forms, including cacti, for example, illustrate that convoluted, finned and ribbed forms significantly increase surface area but at the same time using these types of forms may actually in themselves increase the potential for dew collection. Ribbed and finned forms, in particular, act as radiators and by being more effective at radiative cooling, like various cacti, will facilitate dew formation. It is clear that radiative cooling to the sky is a necessity for dew collection, but this research suggests (Figure 11) that it should be possible to optimise a ribbed/finned surface which 1) maximises surface area, as well as 2) facilitating maximum radiative cooling to the open sky. The ribs and fins also create a slightly altered airflow dynamic which appears to be conducive to greater

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[1] Extracted from Engineering Toolbox. com and infrared-thermography.com

cooling and thus an increased potential for dew formation. The issue of wind speed and airflow and whether this helps or hinders dew forming is not absolutely clear in the literature, but it appears that some airflow (1- 4 meters/second and even possibly up to 6 metres/second) is helpful in creating dew under the right atmospheric conditions. This idea is advanced with a brief look at the literature on the Namibian tenebrionid beetles, which collect fog on their carapaces. This paper considers that the shape of the beetle is very much like an airfoil, and simulates an airfoil in its interaction with moving air. It is suggested that airfoil shapes could enhance dew collection through cooling which is created by the slight movement and splitting of the air below and above the airfoil body. The slight pressure differentials create cooling and thus water condensation. It is thus proposed that even rather small changes in the microclimatic conditions around an object can enhance or deter dew formation and potential harvesting is enhanced by the hairs, spines, thorns and needles of cacti and other plants, especially desert species. It is also mooted that corrugations, which are often found in nature, (leaf veins and ribs and insect wings), which are similar in part to ribs and fins could also play a part in improving the potential for dew to form. Spiny, spiky and lanceolate forms, furthermore significantly increase surface area as well as alter airflow and as in nature (cacti and other plants) these types of protrusion increase the palette of possibilities for dew collection.

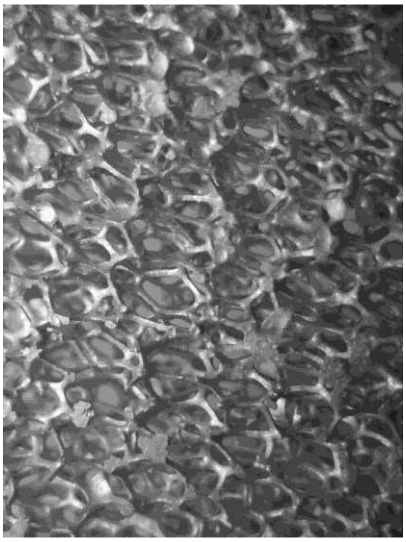

Figure 12. Aluminium organic foam showing dew formation

Maximising radiative cooling is essential for enhancing dew formation and this research has identified that high emissivity materials have a part to play in this. These materials and coatings, which are most efficient in absorbing as well as discharging radiation energy, have not yet been fully explored although some encouraging results have been achieved by others (Nilsson et al., 1994 and Muselli et al., 2002) with titanium dioxide (TiO_2) and barium sulphate ($BaSO_4$ also known as blanc fixe). The use of TiO_2 is interesting because it has a relatively high emissivity value of (0.94) and yet it white in colour. The commonplace idea that all high emissivity materials are dark or indeed black in colour is not correct for glass and water for example have high values.

In this research, the cellular rigid, organic foam type forms were the most successful at dew collecting (Figure 12). Nine out of the first twenty forms were organic foam types and one was of a rigid hexagonal cellular construction. Seven of the first twenty forms were those with spiky/lanceolate projections. Four successful forms had bendy thermoplastic / rubber organic projections whilst three had rigid plastic or stainless steel spikes on a plastic base in the form of bird deterrent spikes. Of the first twenty shapes, one was planar, one was finned and one was linear and string like. Aqua One Sea Grass, which is a decorative product made for aquaria and manufactured out of polyethylene was placed first and tenth as dew collectors (Figure 13).

Figure 13. Thermoplastic rubber ‘seagrass’ showing dew formation on stems

It is interesting to note that polyethylene like most plastic has a relatively high emissivity value. The product, which simulates sea grass [2] has multiple elongated grass like blades that significantly extends the surface area of the collector. As a single unit (Figure 13) the product collected 35.24 ml/m^2/hour when placed vertically and thus it may be theoretically possible to collect approximately 140 ml/m^2/hour if placed at 30°. The collection of 140 ml/m^2/hour appears reasonable when taking account of Monteith’s theoretical maximum

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[2] Seagrasses resemble terrestrial grasses in form. They usually grow in sheltered coastal shallows (photic zone) as they must photosynthesize and are anchored in sand or mud bottoms.

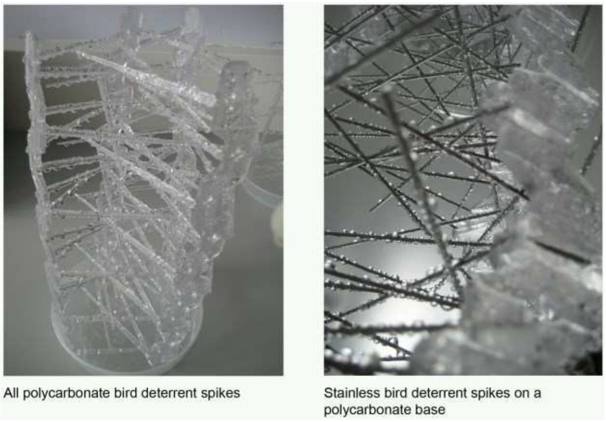
of 133 ml/m^2/hour calculated by the author over a 6 hour period and the amounts collected by Sharan in India. The strings of monofilament fishing line was the second most successful with a figure of 31.72 ml/m^2/hour with a potential for 126.8 ml/m^2/hour. The nylon strings were aligned in a V shape over a box frame (Figure 14).

Figure 14: Nylon monofilament strings showing dew collection on the strings and flow into the collecting dish.

The rigid plastic and stainless steel spikes set on plastic bases were also successful and were placed 5th and 6th in the dew collecting hierarchy. They collected a maximum of 18.92 ml/m^2/hour and 16.63 ml/m^2/hour with a theoretical maximum of 75.68 ml/m^2/hour and 66.52 ml/m^2/hour respectively. The forms used were bird deterrent spikes made from UV stabilised polycarbonate bases with UV stabilised polycarbonate or stainless steel spikes (Figure 15).

The foam type materials were the most successful in this research. Nine of the first twenty best performing forms were made from open celled materials with various sizes of open irregular skeletal like connections, which form irregular interstices. Five of these were made from reticulated vitreous carbon foam, three from aluminium foam metal[3], and one from ceramic foam [4]. One additional cellular product performed 8th best out of all the experiments. This was an open cell polycarbonate hexagonal product extracted from a sandwich type building panel. A number of the UV stabilised polypropylene artificial lawn products tested proved successful. Tests of 24 mm and 21 mm height artificial lawn products performed well and performed 9th and 17th overall with 14.84 and 11.81 ml/m^2/hour.[5]

Glass and water, chosen because of their high emissivity values (the water was contained within two panes of 4 mm thick glass panes with silicone sealed edges) were two of the many forms and materials tested in the dew simulation chamber.



All polycarbonate bird deterrent spikes

Stainless bird deterrent spikes on a polycarbonate base

Figure 15: Two biomimetic cacti (thorn like) forms showing dew formation on the spikes and bases.

These materials were not however, as successful at facilitating and capturing dew as some others. The spiky, lanceolate forms, which imitate the spines, thorns and needles on cacti and other plants, tended almost predictably, to be good at collecting dew. Cacti and some plants such as *Tamarix* species achieve this in nature and thus should do so in the laboratory as well. However, what was not envisaged was how proficient the open pored foam materials would be in collecting dew. This is a revelation and the results are encouraging and tie in appropriately with the concept of semi-passive dew collection where people could extract the precipitation once it has been formed.

Other notable forms and materials that were efficient dew collectors compared to others tested in the dew simulation chamber included nylon monofilament line and artificial lawn. It should be noted that the experimentation with forms and materials in a dew chamber, which was designed for plant pathology purposes was not ideal, but the method allowed at least for a comparative study of performance. It should also be noted that due to the relative small size of the dew simulation chamber and the restrictions this had on the size of the forms tested this research was always conceived as a first stage in the development of life sized dew collection forms and apparatus. This research has established a number of previously unexplored paths. This would include the in situ testing of life size semi-passive systems and the further investigation in particular of spiny, ribbed and finned forms as well as organic foams and high emissivity materials.

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[3] ERG Duocel – These foams are usually used in high technology aerospace and defence industries.

[4] R3 Diffusion – Usually used in architectural situations such as lighting surrounds.

[5] ‘Leisure Lawn’ by the Artificial Lawn Company (24 mm) and Artificial Grass Ltd. (21 mm).

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[i] The use of Monteith (1957) by numerous authors is confusing as he does not discuss maximum dew condensation rates. In the conclusion of his 1957 article he rather states that 'distillation rates could approach 7 to 8 mg/cm^2/hr in English summer or autumn weather.' Using these rates it could theoretically be possible to obtain 420-480 ml/m^2/6 hour night, 560-640 ml/m^2/8 hour night, 600-800 ml/m^2/10 hour night and 840 – 960 ml/m^2/12 hour night. But these figures refer to crop leaf cover and particular soil characteristics.

[ii] 11 November 2009

[iii] This is not enough for the needs of one person but in dry areas this supplementary addition could be beneficial. The World Health Organisation suggests that depending on the climate and individual physiology a person needs 2.5-3 litres per day. (WHO, 2004)

[iv] Dew simulation chambers are normally used in the field of plant pathology to investigate the effects of dew (usually associated with the spread of diseases) on various plants. The dew simulation chamber used was located at Imperial College London, (Silwood Campus) and was manufactured by Mercier Scientific. The author is grateful to Dr Simon Archer and Imperial College London for making the equipment available for this study. The chamber works by inducing water droplets to form on plants or other materials following the principles of natural dew formation. This is accomplished by the location of an inner stainless steel chamber, which is set at a higher temperature than an outer chamber, (at a lower temperature), which acts as a heat sink. Heated, distilled water located in a tank at the bottom of the inner chamber provides the required humidity in the inner chamber. Heat is radiated away from the plants or other materials, placed on open wire racks in the middle/top of the inner chamber, inducing dew point and condensation to form on their surfaces.

[v] Passive in this sense means without the introduction of additional human and/or mechanical energy to extract water from the atmosphere and with minimal intervention by people post the construction of the apparatus. Collection usually relies on the force of gravity.

[vi] The accumulation of gases, liquids, or solutes on the surface of a solid or liquid. (http://www.thefreedictionary.com/adsorption)

[vii] Tree shelters are used to protect trees and shrubs mainly from rabbits. They are usually cylindrical and are placed around the plant and fixed in place with a timber stake.

[viii] Cohen and Rubner at MIT have investigated the bumps of the beetles and have created super hydrophobic materials to aid

[ix] It is also interesting to note that numerous past and present aeroplanes have been designed with corrugated wings, which provide structural stability but also may positively affect drag and perhaps increase condensation.

[x] After the Italian mathematician Leonardo Pisano Bigollo (c. 1170 – c. 1250) also known as Leonardo of Pisa.

[xi] Note: All cacti are succulents, but not all succulents are cacti.

[xii] Succulents utilise crassulacean acid metabolism (CAM) to survive. Carbon dioxide (CO^2) is taken up by the open stomata at night, in the dark, when temperatures are low. The CO^2 enters the chlorophyll containing cells (the chlorenchyma) and incorporated into simple organic acids. With daylight the stomates close and light energy is captured by the chlorophyll containing chloroplasts in the cell where the CO^2 is split off from the organic acids and combined with other simple organic compounds to make sugars. During the day, the increase facilitates a greater uptake of PAR (photosynthetically active radiation) on the whole, but decreases the PAR per unit surface area. At night the greater surface area increases CO^2 uptake on the whole but decreases the uptake per unit surface area. But with an increase in surface area and thus stomates, there is a significant increase in transpiration at night when the stomates are open.

[xiii] The exact process by which the earth loses heat is rather more complex than often portrayed. In particular, convective transport of heat, and evaporative transport of latent heat are both important in removing heat from the surface and redistributing it in the atmosphere. ('Radiative Cooling', Wikipedia.)

[xiv] TiO_2, $BaSO_4$, SiO_2 = titanium dioxide, barium sulphate (also known as blanc fixe) and silicone dioxide (silica) respectively