AIRDRIP© Pneumatic Fog Collector For Rural And Urban Environments In Arid Lands

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***Abstract*—According to the Global report on Human Settlements (United Nations Human Settlements Programme, UN-Habitat, 2003), "almost one billion people, or 32 per cent of the world's urban population, live in slums". Desertification is an additional water challenge manifested in agricultural shortage; demographic shrinkage of settlements and rural migration. To illustrate this large-scale water condition, the Organisation for Economic Cooperation and Development have estimated that by 2030 47% of the world's population will live in water-stressed regions [1].**

Worldwide slums are facing a massive problem of water collection, harvesting and distribution, in arid coastal context. The challenge is to design autonomous water-making devices able to decentralise the monopoly of water supplier and the dependence of the main grid.

Water provision is a fundamental challenge in many rural and slums settlements in arid lands today. The risks associated with water shortage increase as the limited freshwater resources gradually diminish resulting in ineffective central water distribution. AIRDRIP© is a pneumatic air-frame water collection technique by using pneumatic space-frames and nets. In essence, this technology traps and harvests water in coastal deserts through a passive process of fog condensation. The collected water can be directly used for drinking and sanitation (prior water purification) as well as in green public spaces and urban agriculture.

This study proposes an inflatable three-dimensional fog collector, which harvests fog water for drinking, agricultural irrigation and ecological restoration. Both a space-frame polyhedral structure and hydrophobic net was preliminarily tested in the Atacama coast, Chile (FOGHIVE, 2014) in order to increase water yield in arid contexts. However the main obstacle for many fogtraps is the intermittence of winds and fog occurrence. In order to achieve water intersection and therefore harvest it, AIRDRIP© has to face wind multi-directionally; improve drainage system and augment mesh surface to capture atmospheric water. In the case of the Camanchaca phenomenon (Atacama Desert), its mesh offers specialised textile pattern and filaments; water-repellent features; and multi-directional wind-faced array. This new design demonstrates the simplicity of tubular air-frame beams and rings, ballast tank and strap connectors.

Rather than a prescriptive design, AIRDRIP© is an open system that stimulates future colonisation scenarios in arid lands. It stimulates the autonomy of local communities against the unbalanced control and distribution of water in poor countries by facilitating the right to clean water at any societal level. AIRDRIP© design is mainly focused on eco-design materials and techniques by reusing industrial polymers through remaking or other media.

This research offers a radical design for pneumatic fog collection in urban and rural settlements along the Atacama coast (Coquimbo region, Chile) and other similar climates on Earth.

***Keywords*—Fog collection; autonomous water management; water shortage in arid settlements; pneumatic space-frames; rubber remaking**

I. PREAMBLE

Right to water is in the environmental agenda of many communities worldwide. Desertification is the result of a neglectful manned use of land resources. Alternative water supply strategies [2] are required for the mitigation of future global starvation, rural migration and even wars as water resources are mainly employed in agriculture or mining. Regarding the future global pressure of water, the *United Nations World Water Development Report* has estimated that by 2030 47% of the global population will live in water-stressed region [3]. Hence a sustainable water management protocol is urgent in many settlements, mainly along the Pacific coastline of the Atacama Desert frequently attacked by earthquakes and seasonal droughts.

AIRDRIP© is a pneumatic technology of fog collection that offers an agile solution to increase water yield in fog oases along arid coastal contexts. It has recently been validated via a proof of concept via form, coating and water tests in the Region of Coquimbo, Chile. AIRDRIP© traps and harvests atmospheric water in coastal fog oases through condensation on light coloured hydrophobic meshes supported by an inflatable space-frame. The collected water can be directly stored and used for drinking, agricultural irrigation (including urban parks) and restoration of endangered ecosystem.

The applied method is research by design, supported by literature review; climatic and structural simulations; mock-ups and prototype; and fieldworks. The hydric, structural and spatial capacities of this 3D fogtrap system can help ecosystem restoration, agricultural innovation and autonomous potable water distribution in water-stressed regions in rural or natural environments along the Atacama Desert coast (Coquimbo region, Chile) and similar scenarios.

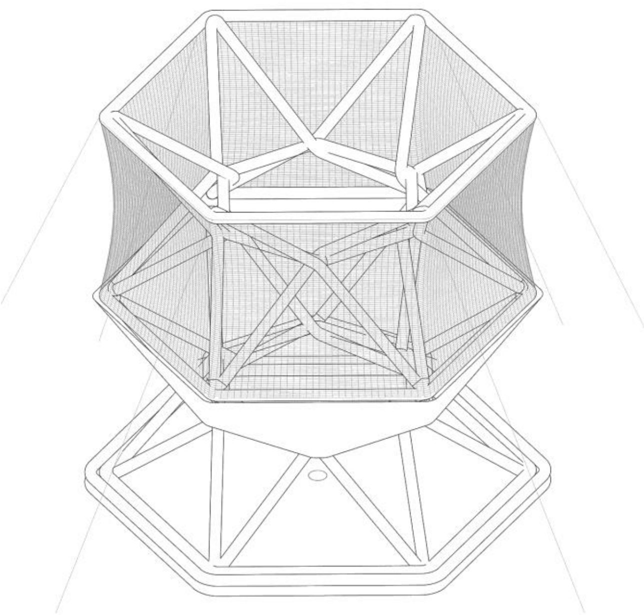

Fig. 1. *AIRDROP©: Axo-view of inflatable frame. Source: Suau & Zappulla, 2015*

Pioneering passive fog collector structures (planar versions) were developed in 1950s in Chile [4]. Both standard and large fog collectors have been deployed as an alternative water source in dry areas with frequent dense fog events. The screens are either double-layered agricultural net or vertical Teflon strings for smaller cylindrical devices [5]. These two-dimensional frames only face the prevailing wind direction, so loss is massive. Advanced coating solutions have been experimented but there is still a lack of applicability.

Fig. 2. *FOGHIVE© facing fog occurrence in Peña Blanca at dusk (Atacama, Chile). Source: Suau, 2015*

By comparing all the limitations of the previous designs, AIRDRIP© is an innovative passive 3D fog collector able to collect fog water multidirectionally and harvest for drinking, agricultural irrigation and ecological restoration. It resolves water scarcity in remote areas in arid contexts throughout a smart pneumatic space-frames and 1:1 ratio screens. This design is an upgraded and integrated version of previous 3D fog collection technologies: (a) FOGHIVE© [6] invented by Dr Suau (2010; 2013; 2014) and built in lightweight timber frame (2014) and (b) AIR ART© [7], a DIY pneumatic structure based on attachable triangular air-frames (Suau & Zappulla; 2013, 2014).

II. METHODS AND EXPERIMENTS

The research method applied is practice-based design. The design precedents are FOGHIVE© (Suau, C. 2010, 2011, 2014) and AIR ART© (Suau, C. & Zappulla, C., 2012, 2014). The transdisciplinary aspects of AIRDRIP© design integrates eco-design, pneumatic structure, ecology, climatology, hydrology and materials science. The design research methods include:

- *Literature review:* Study of fog collection types implemented in arid coasts mainly in South America and Europe.
- *Climatic analysis:* Climate data collection to identify potential fog oases in the Region of Coquimbo, Chile. Data was provided by Centro de Estudios Avanzados en Zonas Aridas (CEAZA), Chile [8]. Fog occurrence is intermittent in August.
- *Textile tests:* The initial sampling on surface area and adsorption parametres of thirteen meshes were implemented at Strathclyde University, Department of Chemistry by Dr Ashleigh Fletcher (2014).
- *Mock-up structural design:* Preliminary prototypes were constructed and tested at the University of Strathclyde and ECOFABRICA in 2014. The each tested screen was 1m x 1m area. The six sides are elevated two metres above the ground level and compare with conventional planar fog collectors. An alternative polyhedral form was successfully erected in the Region of Coquimbo (Chile) last August 2014.

- *Digital design:* Parametric design included tri-dimensional models, technical drawings and component. The digital design softwares applied are RHINO, AutoCAD, Google Earth and Adobe Creative Suite CS4.
- *Fieldwork:* Site visit and scientific meetings with local experts, industry and community; and proof of concept in the fog oasis Peña Blanca, Coquimbo Region (Chile): 30° 53' 46" S, 71° 35' 31". This remote fog oasis was selected for its atmospheric hydric capacities. The site is remote, has endangered native low flora and is in the vicinity of the rural settlement.
- *Water quality test:* Fog water was collected from Peña Blanca on 13 August 2014 (nocturnal fog occurrence) = 4.70 $l \times m^2 \times day$. Sampling and chemical and microbiological analysis of water samples took place in Santiago de Chile at Manuel Ruiz Laboratory (report issued on 17.11.2014).

III. HORIZONTAL PRECIPITATION

The notion of horizontal precipitation (HP) –also known as fog oasis or cloud forest- is directly connected with dense atmospheric water content, which includes both fog and dew occurrences. HP refers to flora that grow by drawing moisture directly from cloud formations. Geographic obstacles with high elevation stop the fog flows and form fog oases as outlined in the HP worldwide occurrence's figure. In the case of the Coquimbo Region, it offers great concentration of fog occurrence along all year (CEAZA MET, 2015). Relative humidity (RH) reaches values above 90%.

A great example is the Fray Jorge National Park, is a great example of cloud forest anchored in the Chilean Coastal Range of the driest desert on earth. It lies approximately 100 km south of La Serena city. This park covers an area of circa 100 km and only 4% is covered by forest (Valdivian temperate rain forest). The *Camanchaca* (coastal fog) hangs on the cliffs and mountain slopes and moistens subtropical vegetation, allowing the forests to survive despite being surrounded by semi-arid scrublands, with average annual rainfall of approximately 113 mm. The forest is a vestigial survival of the last glacial period.

Adaptable flora have evolved to survive in fog oases along arid contexts by developing water-repellent skins in leaves or stems and their micro-filaments to catch atmospheric water from all wind-faced directions such as bromeliads, *Aristolochia chilensis* (Oreja del Zorro in Spanish) and *Calandrina Logiscapa* (Pata de Guanaco in Spanish) in the Atacama Desert, Chile; *Pinus Canariensis* in the Canary Islands, Spain; and the grass *Stenocara Gracilipes* in the Namib Desert, Namibia. Their natural forms and surfaces offer smart common features to be replicated: (a) specialised filaments (i.e.: trichomes); (b) water repellent or hydrophilic surfaces; and (c) multidirectional wind-faced geometry.

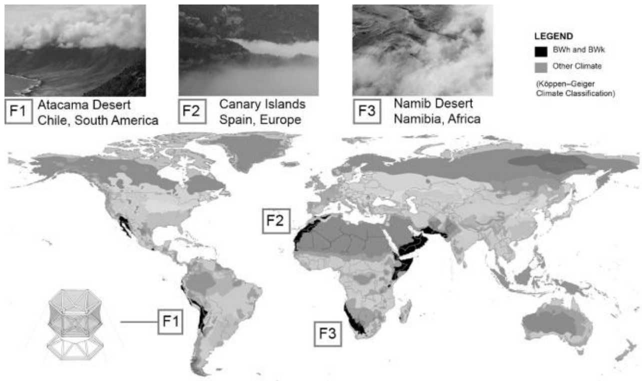

Fig. 3. Worldwide Fog Occurrence. Arid areas with coastal fog are marked in black. Source: Suau, Zappulla & Duncheva (2015).

IV. SITE CHOICE AND INSTALLATION

The *Camanchaca* (coastal fog) occurs in multiple locations along the littoral of the Atacama Desert and specifically Coquimbo Region, Chile. (Cereceda, 2011). Most of the high-populated coastal settlements such as Iquique, Taltal, Antofagasta, La Serena and Los Vilos are situated between 0-25m above the sea level and nearby fog events. In the case of these coastal settlements, the altitude difference between highland fog formations and lowland (400-700 metres) results in economic and logistic challenges for fog collection. The prevailing wind direction is SW and the average RH is 87% and wind speed 3.6 m/s (average).

After several fieldworks in the North of Chile, Cerro Grande site in Peña Blanca (Coquimbo Region) was selected to carry out the proof of concept [9]. This remote rural site (protected area) includes endangered local low flora and seasonal grazing. The site is situated 8.52 kilometres away from the coastline. It is elevated 622 metres above sea level.

Both geometry and water harvesting capabilities of were tested during three consecutive days in August 2014 (Suau, 2014). This is a lightweight and modular timber space-frame wrapped with light colour hydrophobic mesh to intercept fog water. It performs also as a shading device and soil humidifier for greenery and crop. The montage of this hexagonal space-frame took six hours and demounting time was two hours. Only two people can assemble it.

V. AIRDRIP©'S MORPHOLOGICAL, TEXTILE AND WATER QUALITY TESTS IN THE ATACAMA DESERT

This section releases the design conditions for AIRDRIP© regarding form, fabric choices and water quality test in the chosen fog oasis in the Region of Coquimbo (Chile) and its applicability in remote places elsewhere.

Form and Air-frame

The eco-design objectives of AIRDRIP© are: (a) to augment water yield efficiency in mesh types and form; (b) to optimise the structural stability through pneumatic space-frames; (c) to minimise the environmental and visual impacts on the immediate surroundings; (d) and to envision future inhabitation as autonomous water harvesters. The hydric, structural and spatial capacities of this agile system can serve ecosystem restoration, agricultural innovation and autonomous potable water distribution in water-stressed regions in urban, rural or natural environments.

AIRDRIP© is a lightweight, demountable, modular and pneumatic 3D fog collector. Following a study on the aerodynamic flows of different geometric configurations (circle, triangle or square shapes), a hexagonal array was selected (Suau, 2010, 2012). This technology has a screen ratio of 1:1. This polyhedral air-frame uses simple components and fixtures. Essentially its polyhedral form faces all wind directions in order to increase fog water collection. AIRDRIP© is an upgraded pneumatic version of FOGHIVE©. It offers both structural frame and mesh improvements through lightweight air-frame (double rubber layer); modular prefab chunks (air rings and beams); drainage mesh (copper wired mesh); embedded water storage (ballast tank); pump; and strap connectors.

The key design challenge of AIRDRIP© (and any fog collector) is to provide flexibility to trap and harvest water in discontinuous scenarios of fog occurrence by increasing its mesh surface and thus fog water yield. In doing so, AIRDRIP develops an optimal form that follows the wind rose's wind direction. Its layout is divided in six zones (cardinal directions) that face the frequency of winds - direction and speed- blowing from all directions over a specific season.

Mesh Experiments and Fabric Selection

Various samples of polymer mesh have been studied regarding the surface area, texture, patterns and porosity. Complementary features that augment fog collection are: (a) light colour that increases condensation; (b) filament geometry (pattern making); and (c) affordability (pricing). The selected samples demonstrated mesoporous properties. Mesopores (pore diameter between 2 and 50 nm) can trap small water droplets, which increase chances for water particle coalescence.

On contrary, microporous properties (pore diameters of less than 2 nm) are considered negative for fog collection due to they are not able to retain water droplets and prevent coalescence. All chosen samples demonstrated poor thermal stability for use in direct sunlight. Two types of water-repellent fabrics were selected and tested in all screens: (a) white polyethylene UV stabilised insect mesh and (B) 3D polyester textile FogHa-TiN.

Mesh Experiments and Fabric Selection

It was expected that the 3D polyester fabric applied in planar screen would obtain a higher water absorption performance due to its filaments and porosity values. Paradoxically the in-situ proof of concept polyhedral choice with six screens harvested equal amounts of fog water regardless the selected mesh types (four insect meshes vs. two 3D ones). As result the overall water absorption performance suggests that the hexagonal base frame can yield fog water evenly due to the multi-directional wind response of this shape.

The experiment revealed that affordable insect mesh screen (light colour) could be applied in future implementations. Fog water was collected from Peña Blanca *lomas* on 13 August 2014 (dry season) during nocturnal fog occurrence only. Each screen (six in total) obtained 8,70 $l \times m^2 \times day$; total 52,20 $l \times m^2 \times day$. Sampling of water chemical and microbiological analysis took place in Manuel Ruiz Laboratory, Santiago de Chile: http://www.mrlab.cl (report issued on 17.11.2014).

The water analysis of chemical elements indicates a pH of 6,48; almost neutral (7 pH scale). This analysis confirms that the collected fog water from Cerro Grande fog oasis does not contain toxic chemicals. Therefore water is suitable for drinking and irrigation without any treatment.

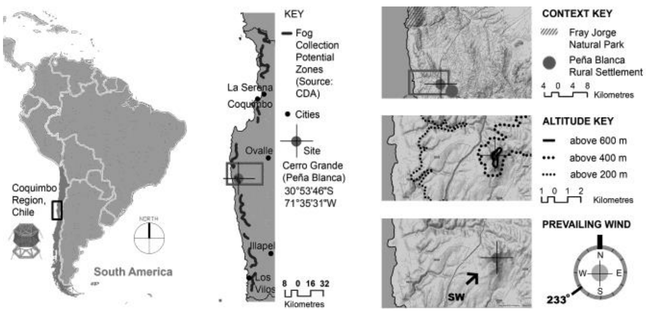

Fig. 4. Geographic location of Cerro Grande in Coquimbo Region. This chosen fog oasis offers adequate climatic and geographic conditions for fog collection. Source: Suau & Duncheva (extracted from Cereceda et al, 2011)

Water Quality Test

The chemical composition in fog water is crucial. Hence it was imperative to verify the water quality collected by this device and excluding the presence of harmful constituents. Due to the remoteness of this site (far away of coastal urban settlements or mining areas) we found low levels of contamination in 13 toxics elements. Bacterial evidence was not found in the water test.

Six 1m x 1m fog-water collector meshes and six plastic water containers (up to 10l capacity each) were used on site to study the incoming fog. The meshes rapidly clean themselves from any dust deposition.

The trace-element concentrations met Chilean (NCh) and the World Health Organization's (WHO) drinking-water standards. Solutions with a pH less than 7 are acidic and solutions with a pH over 7 are alkaline or basic.

The water pH level obtained roses 6.48 (neutral), which meets the drinking-water standard. So the analysed trapped fog water is a viable alternative as water supply in the selected fog oasis.

The sampling was carefully collected in six portable plastic tanks (polyethylene terephthalate); stored in portable refrigerators and transported in 4WD vehicle from fog oasis to lab; and finally analysed by an independent accredited laboratory called 'Laboratory Manuel Ruiz Ltd.' (http://www.mrlab.cl) in Santiago de Chile.

WATER ANALYSIS REPORT FROM CERRO BLANCO FOG OASIS*

CHEMICALS PARAMETERS	UNIT	WATER SAMPLE	MAX. LIM. NCh 1333 Of.78	ANALYSIS DATE	TIME	ANALYSIS METHOD
PH	u pH	6,48	5,5-9,0	18-11-14	17:10	NCh** 2313/1 Of.95
aluminum	mg/L	0,2	5,00	18-11-14	15:00	SM 3111 D
arsenic	mg/L	0,004	0,10	18-11-14	15:30	NCh 2313/9 Of.96
barium	mg/L	<0,1	4,00	18-11-14	15:00	SM 3111 D
beryllium	mg/L	<0,1	0,10	18-11-14	15:00	SM 3111 D
cadmium	mg/L	<0,005	0,010	18-11-14	15:00	NCh 2313/9 Of.96
cobalt	mg/L	<0,02	0,050	18-11-14	15:00	SM 3111 B
copper	mg/L	0,02	0,20	18-11-14	15:00	NCh 2313/10 Of.96
total iron	mg/L	0,21	5,00	18-11-14	15:00	NCh 2313/33 Of.99
lithium	mg/L	<0,02	2,50	18-11-14	15:00	NCh 2313/33 Of.99
manganese	mg/L	<0,01	0,20	18-11-14	15:00	SM 3111 B
mercury	mg/L	<0,001	0,001	21-11-14	14:30	NCh 2313/10 Of.96
molybdenum	mg/L	<0,01	0,010	18-11-14	15:00	SM 3111 D
nickel	mg/L	<0,02	0,20	18-11-14	15:00	NCh 2313/10 Of.96
silver	mg/L	<0,01	0,20	18-11-14	15:00	SM 3111 B
lead	mg/L	0,02	5,00	18-11-14	15:00	NCh 2313/10 Of.96
vanadium	mg/L	<0,1	0,10	18-11-14	15:00	SM 4500
zinc	mg/L	0,06	2,00	18-11-14	15:00	NCh 2313/10 Of.96

* Water quality test: Fog water was collected from Peña Blanca on 13 August 2014 (nocturnal fog occurrence) = 8.7 lxM2xday. Sampling and chemical and microbiological took place at the Laboratory Manuel Ruiz and Company Limited Santa Elena http://www.mrlab.cl. No. 1209, Santiago de Chile.

** NCh: Chilean standard regulation based on SO/IEC Directives, Part 1:2009 Procedures for the technical Work.

Fig. 5. Drinking water quality analysis from collected samples in AIRDRIP©. Source: Laboratory Manuel Ruiz Ltd., Santiago de Chile

VI. AIRDRIP©: AIR-FRAMES AND COMPONENTS

Polyhedral geodesic form offers a very efficient structure due to its triangulation array and harmonious material-to-volume ratio. We incorporates this design principle into the development of AIRDRIP©. Its technology enables to inflate the air-frame –both hexagonal rings and flexi-tubes- in few steps.

Both hexagonal rings and zig-zag air-beams interweaves. Once inflated, the air-frames can be divided into separate air chambers or chunks that ensures additional structural stability in the event that any chunk becomes damaged whilst all the other air-beams still remain stable.

The malfunctioning part can quickly be repaired or replaced. This pneumatic structure is modularly built with a doubled layer air-beams to allow structural reinforcement and prevent animal attacks. This ensures an exceptional stability and an easy installation in remote milieus.

- *Air-frame: Rings and Beams*

Double layer fram: The air-beams (two types; 4+3 units) are built with a resistant double-layer of butyl rubber (outer layer) and polyester (inner layer): 100mm□□□□total length 1150mm and 1700mm respectively. The air-rings (two types; 2+1 units) are also built with the same resistant double-layer system: 100mm□□□□total length 597.5mm and 1119mm respectively. The inner layer or tube (optional) is made of polyester or nylon fabrics.

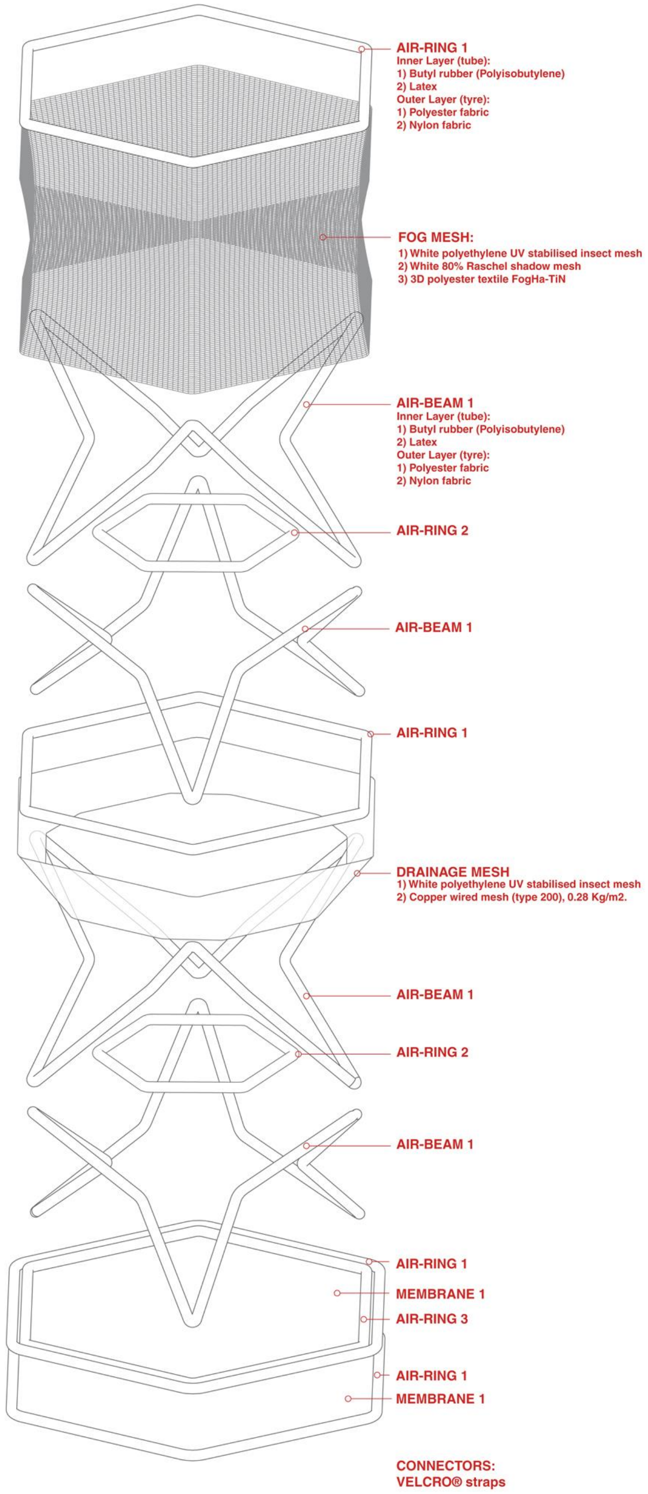

Fig. 6. Exploded axonometric view of AIRDRIP© 3D fog collector with its components and materials. Source: Suau & Zappulla

The bladder keeps the air inside for a long time. It provides protection and stability. During heavy winds, use guylines tensioners for structural stability.

2-in-1 valves for inflation and deflation: The 2-in-1 valve is allocated in every air chamber with two closures: a valve is for quick and simple inflation of the air-frame and an opening valve for easy disinflation. Hence mounting and pull-to-pieces processes are simply done.

- *The Fog Mesh*

The total area is 21,4 m^2; each screen area is 3.57 m^2. Based on the best performance of selected fabrics we suggest the application of white polyethylene UV stabilised insect mesh.
Alternatively you can also install white 50-80% Raschel shadow mesh (affordable version) or 3D polyester textile FogHa-TiN [10] (sophisticated option).

- *The Drainage Mesh*

The total area is 11 m^2. If the bacteriological level of trapped fog water is high we utilise a copper wired mesh (type 200; wire 0.05mm and weight 0.28 mm). Otherwise we use a microporous membrane of white polyethylene UV stabilised insect mesh.

- *The Water Storage (ballast tank)*

To minimise water loss the water storage is situated underneath the drainage mesh. The water is stored in a cavity between two latex membranes (total area: 10 m^2). If the base tank is full, a transmission pipe is connected to supply water to large cisterns by using gravity. This water is then fed to taps for domestic and agricultural use. Structurally it also acts like a blowfish or ballast to provide foundation stability.

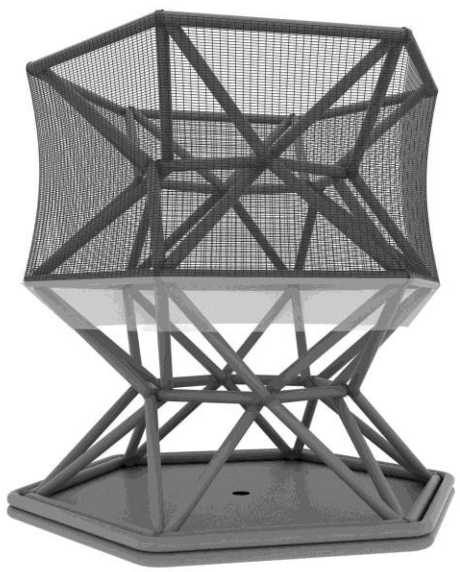

Fig. 7. AIRDRIP© model (digital view). Source: Suau & Zappulla, 2015.

- *Pump*

Double action pump is applied in AIRDRIP© valves. It is armed with a metal piston, which allows durability and manoeuvre.

- *Installation, Disassembling and Repair*

Inflating acts intuitively by following a basic sequencing: unroll, inflate, strap and wrap. The stages are: (1) unroll the fogtrap; (2) close all valves; (3) choose any of the valves; (4) and pump air with any standard pump. Dismantling works very quickly too. Simply open all valve openings and air releases immediately. Extract air out, roll it up, pack it and ship it to the next fog oasis! Like bike wheels each air-beam can be easily patched or replaced. If the mesh damages, it can be replaced as well.

- *Funding and Pricing*

The funding for this technology has been possible through the join-venture of Dr. Suau in recent partnership with Dr. Zappulla. Both IP and copyright belong to them.

Regarding manufacturing costs, the commercial price of this set is $1850 USD (excluding shipping and delivery fees). The production cost varies if it is locally manufactured or not. For instance, the manufacturing costs roses in China $425 USD per unit (minimum 100 units).

VII. DESIGNING FUTURE APPLICATIONS

The specific geologic features of the coastal formations along the Atacama Desert and particularly the context of Cerro Grande (case study) offer great potential applications regarding water harvesting for drinking (rural settlement), agricultural irrigation (*'fogponic'* farming) and ecological restoration by protecting native flora and fauna [11]. This strategy should combine innovative water management strategies in arid environments that take into account traditional water techniques for irrigation such as terrace farming made by Incan agriculture and Arab water irrigation systems or *qanāt* (Laureano, 2001).

A transect section of alternative water provision system illustrate a terraced water distribution scheme driven by using gravity as water transport media. The collected fog water could be distributed through two independent pipelines: (a) the main pipe connecting the top cliff with coastal settlements for drinking and FOGPONIC© farming, a water fog-based crop system that combines fog collection with sea water (Suau, 2014); and (b) a secondary irrigation pipe for dripping technique to restore native flora and prevent desertification (soil erosion). Thus the overall scheme operates as an entropic water cycle that returns surface water to the atmosphere (coastal fog formations) through evapo-transpiration.

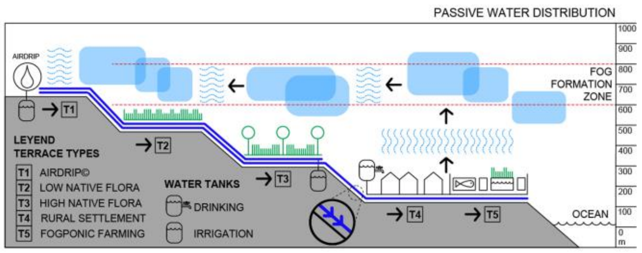

Fig. 8. Sectional diagram of AIRDRIP© water collection and distribution in arid coastal context. Source: Suau, 2015

VIII. CONCLUSIONS

AIRDRIP© technology offers a triple improvement regarding structure, mesh and water yield and harvesting performances. Structurally the key innovation lies in its geodesic structural form and size ratio of the screens that increases the water harvest six times compared to conventional planar fog collectors.

Its lightweight air-frame system increases stability against strong winds by adding a ballast tank as water storage and foundation. It can either be manufactured off-site and distributed in supermarkets or locally customised in tyre repairshops or '*vulcanizadoras*', which decreases its water footprint.

The textile innovation offers an affordable mesh - white polyethylene UV stabilised insect mesh- that can replace the traditional Raschel sunshade fabric or expensive 3D coatings.

Water harvest increases due to the multidirectional wind response of screens that collect and distributed evenly the same amount of fog water. The water analysis of fog water harvested at Cerro Grande reveals that fog water collected from remote sites (detached from urbanisation or heavy industry) contains low level of pollutants and do not need any chemical treatment.

ACKNOWLEDGMENT

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