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Authors
Caldas, Luisa
Andaloro, Annalisa
Calafiore, Giuseppe
et al.

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Water Harvesting from Fog Using Building Envelopes – part I

Luisa Caldas[a†], Annalisa Andaloro[a,d], Giuseppe Calafiore[b], Keiko Munechika[b], Stefano Cabrini[c]

[a] University of California, Berkeley, Department of Architecture, College of Environmental Design
[b] aBeam Technologies Inc.
[c] The Molecular Foundry, Lawrence Berkeley National Laboratory
[d] European Research Academy (EURAC) Institute for Renewable Energy

[a] Corresponding author.[†] Current address: Department of Architecture. University of California, Berkeley, 384 Wurster Hall #1800, Berkeley, CA 94720-1800, USA.

Abstract

New sources of clean water are currently being researched and implemented, to face global water shortage. Techniques such as desalination or cloud seeding can have a high yield but present problems such as excessive energy consumption or consistent environmental impacts. Fog harvesting stands out for being considerably simpler and inexpensive compared to the previous. In the last decades researchers have developed detailed studies and numerical models, supported by a number of successful examples located mainly in arid or seasonally arid climates. This study surveys existing methods to collect water from fog, such as drop coalescence on vertically placed meshes, chemical absorption and desorption, and radiative condensers. Yields from different collectors are compared and some considerations on influencing climatic factors are discussed, suggesting that radiative systems may be applied on building envelopes as collection devices. A follow-up paper will present experimental results on applying radiative collection systems in buildings.

1. Introduction

Water shortage has become critical due to growth of world population and issues like climate change, hydraulic fracturing, increased demand in agriculture, and pollution of water sources caused by rapid and uncontrolled industrial development (Gleick, 2014). Several studies have demonstrated that different regions of the world are already experiencing the first symptoms of water scarcity(Postel, 2000).

Water shortage has become a fundamental issue in the last few decades. Water is a critical component for key human activities, from agriculture and farming to industrial processes and energy production. The constant increase in water consumption makes this problem a priority that governments are forced to face at the global scale (Postel, 2000). The scarcity of available water is further enhanced as a consequence of the Water-Energy-Food Nexus, which represents the close interconnections among the production of these critical resources for every human activity (Gleick, 2014). In fact, modern food production processes are based on the assumption that the amount of accessible water and energy is unlimited. Also, the energy production industry is based on the unconstrained availability of water masses for the production of electricity and hydraulic fracturing for the extraction of natural gas from underground cavities (Gleick, 2014). The water used for agriculture, industrial and domestic uses, comes mainly from rivers, which are renewable water sources that can be easily recharged by actuation of the natural hydrologic cycle of evaporation and precipitation. Nevertheless, global climate changes are menacing the stability of such reservoirs, as precipitation cycles are less stable and predictable (Rockström *et al.*, 2014). As an example, such precipitation anomalies tend to be correlated in the long range for different time lags comprised between four months and twenty-eight years in the Sahel territory(Efstathiou, M.N. & Varotsos, 2012). On the other hand, observed changes in the magnitude and frequency of hydrological cycle variations naturally question the historic assumption on hydroclimatic frequency analysis adding further uncertainty to water resource availability over the years (P.C.D. Milly, J. Betancourt, M. Falkenmark, R.M. Hirsch, Z.W. Kundzewicz, D.P. Lettenmaier, 2008). Non-renewable sources such as groundwater reservoirs are also increasingly being exploited due to growing needs of the global population. From the 1950s, withdrawal amounts from both renewable and non-renewable sources have constantly risen to meet increasing demands (Postel, 2000). This increase is also related to a steady growth in food production registered over the last 50 years, which in turn recalls for an analogous trend in water demand(Krapivin, Varotsos and Soldatov, 2017). In this framework, investigating the potential for water recovery from alternative sources to rain, rivers and groundwater is crucial to allow for more a sustainable and reasonable management of existing natural water resources. In fact, hydrological cycle alteration are expected to generate significant modification in water resources spatial distribution over the years, including but not limited to drinking water (Krapivin, Varotsos and Soldatov, 2017). The exploration of alternative sources of potable water has led to the development of various innovative techniques, such as desalination (Karagiannis and Soldatos, 2008) or cloud seeding (Boucher, 2015). The former consists in the treatment of seawater to remove soluble salts. The latter is a complex technique that forces an artificial alteration of the natural hydrologic cycle. This is done through the use of chemical substances (i.e. dry ice or silver iodide aerosols), which are injected in the air above the level of the clouds to trigger the precipitation of rain. Both of these techniques are not universally applicable. Desalination is a valid option only in coastal countries, and requires a considerable amount of energy for plant operation and significant initial investments (Karagiannis and Soldatos, 2008). Cloud seeding is an expensive and controversial technique, which raises concerns for human health related to the use of silver iodide (Quadros and Marr, 2010). In addition, not all environmental and climate scientific communities agree on the proven efficiency of this method. Furthermore, both of these techniques have high environmental impacts (Wahlgren, 2001), so more environmentally friendly systems are still being sought.

Among all the available water harvesting technologies, fog harvesting has grown in importance in the last years, as a way to provide drinkable water to rural communities (Olivier and de Rautenbach, 2002; Schemenauer, Cereceda and Osses, 2005; 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 interest in the field is enhanced by the number of such installations present in various areas of the world, where fog collectors represent the only source of water for locals during several months of the year (Schemenauer, Cereceda and Osses, 2005).

Successful fog harvesting projects developed in various locations worldwide, have proved that it is possible to retrieve water from fog in geographic regions where precipitations are rare (Klemm *et al.*, 2012). Many examples of fog harvesting collectors produced significant amounts of potable water, compared to the original availability in the specific site and per capita average consumptions (Schemenauer, Cereceda and Osses, 2005). Most of the existing devices are located in arid and seasonally arid climates, such as Saudi Arabia (Gandhidasan and Abualhamayel, 2005, 2012; Sharan, Beysens and Milimouk-Melnytchouk, 2007; Suau, 2010; Rivera, 2011; Hiatt, 2012; Fessehaye *et al.*, 2014)), Chile (Gandhidasan and Abualhamayel, 2005, 2012; Sharan, Beysens and Milimouk-Melnytchouk, 2007; Suau, 2010; Rivera, 2011; Hiatt, 2012; Fessehaye *et al.*, 2014), and California deserts (Gandhidasan and Abualhamayel, 2005, 2012; Sharan, Beysens and Milimouk-Melnytchouk, 2007; Suau, 2010; Rivera, 2011; Hiatt, 2012; Fessehaye *et al.*, 2014), while very few of them have so far demonstrated interesting collection capabilities in colder climates, such as Corsica Island (Muselli *et al.*, 2002) and Sweden (Nilsson, 1996). The locations of such projects are reported in Figure 1.

Figure 1. Map with locations that have reported successful projects of production of fresh water from fog, in arid or seasonally arid regions. (Klemm *et al.*, 2012)

This paper reviews a collection of fog harvesting systems that were tested on real scale projects in different locations of the world. These include, but are not limited to, South America, Middle East countries, South Africa and India. Countries located in the Northern hemisphere do not present many examples of such projects, despite the fact that water shortage has become a significant issue there too, in the recent years.

We propose to bring the concept of water harvesting from fog into the urban environment, through the exploitation of building envelopes as potential collecting surfaces. In this paper, the feasibility of this concept is investigated through a literature review, to outline strengths and weaknesses of existing technologies, and to identify potential for integration in building envelopes. Afterwards, the authors propose a set of experimental results in a separate paper, highlighting crucial aspects in designing an enhanced water collecting yield surface. Although fog collection is an interesting source of water that deserves investigation, authors want to stress that this study addresses only the technical part of fog collection mechanisms, being aware of the complex health related issues that may arise from the use of atmosphere collected water (Ritchie, Richards and Arp, 2006; Lye, 2009; Liu *et al.*, 2012; Schoen *et al.*, 2017)

Integrating fog harvesting systems in the urban environment could support part of water needs in office, institutional and commercial buildings, where end water uses are less significant than in the case of residential use (Mayer *et al.*, 1999; Dziegielewski *et al.*, 2000). This work proposes an innovative development of the fog harvesting technologies used in rural environments to be applied in cities and offer a sustainable alternative for the supply of water rather than traditional sources, avoiding also the environmental risks connected to the use of cloud seeding and desalination. In addition to these advantages, water production would also be local, allowing for consistent savings in the infrastructural system use.

2. A review of systems currently used for fog harvesting

The three most diffused techniques to harvest water from fog are (Figure **2**): 1) drop coalescence on vertically placed meshes (Olivier and de Rautenbach, 2002; Schemenauer, Cereceda and Osses, 2005; Suau, 2010; Holmes, Rivera and de la Jara, 2014); 2) devices that include chemical absorption and desorption processes (Gad, Hamed and El-Sharkawy, 2001); 3) promoting condensation on cold surfaces during the night (Muselli *et al.*, 2002).

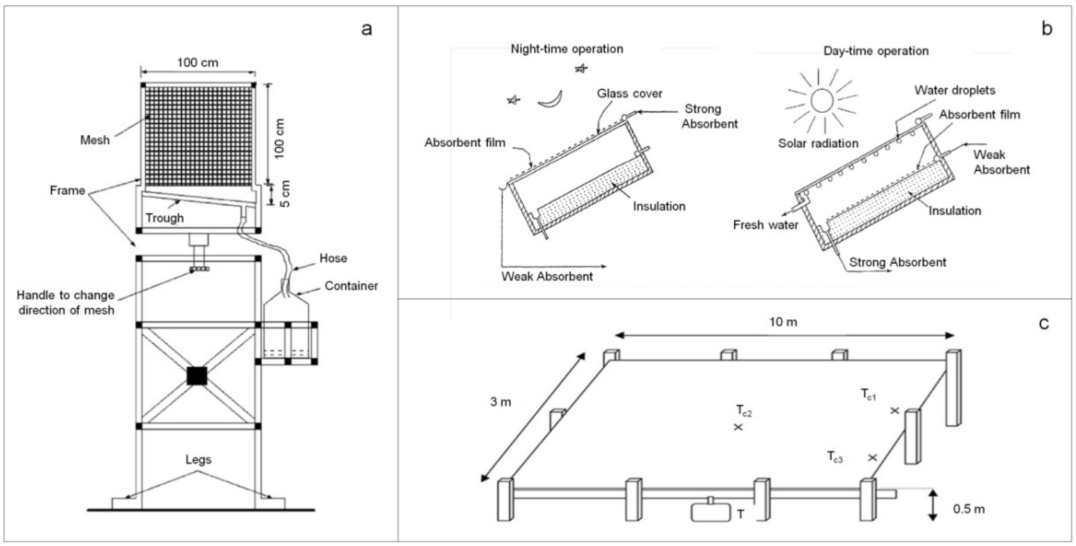

Figure 2. Currently used apparatus for fog capturing. **(a)** Design of a mesh collector system and piping (Gandhidasan and Abualhamayel, 2007; Hiatt, 2012)**. (b)** Functioning scheme of a chemical fog collector (left: night collection, right: daytime release) (Abualhamayel and Gandhidasan, 1997). **(c)** Scheme of a flat fog condenser (Muselli *et al.*, 2002)

Mesh collectors can be divided into two main groups: standard fog collectors (SFC) and large fog collectors (LFC), according to the surface area of the considered mesh (Klemm *et al.*, 2012). The typical size of SFCs is generally 1x1 m, whereas LFCs can reach larger width in size and are usually rectangular, with longer horizontal dimensions, due to aerodynamics. Condensed drops are pulled by gravitational force towards plastic gutters that collect the water and direct it to a tank located on the ground (Fig. 2 a). The tank can also be located at a higher level for maintenance or hygiene purposes (Gandhidasan and Abualhamayel, 2007, 2012).

The most widely used fog collecting mesh is polypropylene Raschel mesh (Klemm *et al.*, 2012). When Raschel mesh was not available on the local market, other types of mesh have been successfully used, as shown in Figure **3**. In fact, building such systems with locally available products has been a key element for the sustainability of this technique in rural communities and developing countries (Olivier, 2004).

Figure 3. Different examples of mesh types for fog collection. From left to right: Raschel's mesh (www-marienberg.cl); stainless and polymer mesh (www.meshconcepts.co.za); three-dimensional net structure mesh made of polymers (www.itv-denkendorf.de) (Klemm *et al.*, 2012)

Work is currently being performed on the possible optimization of mesh yield through the application of lubricant coatings to the fibers, exploring the fact that hydrophobicity makes condensation phenomena more intense (Yu *et al.*, 2012; Lalia *et al.*, 2013; Smith *et al.*, 2013) or just by means of geometric optimization of the mesh fibers (Park et al., 2013). However, these efforts are still undergoing laboratory development and testing, and more work needs to be performed to assess their full potential as products.

Figure 2 b shows a different type of system to harvest water, called a chemical collector, which is based on absorption and desorption mechanisms of a desiccant placed in a specifically engineered structure (Gandhidasan and Abualhamayel, 1996). The device has a rectangular cross-section and is mainly made of a heat-insulating layer (bottom) and a glass cover (top) that are separated by an air gap of 45 cm. The device functioning is based on the combination of two phases: water is collected during night and solar radiation during daytime is used to distillate the absorbed water (Abualhamayel and Gandhidasan, 1997). A thin layer of desiccant is flown on the glass surface during night, which forms an absorbent film to enhance fog capturing. Calcium chloride is generally used as an absorbent because of its low toxicity, reduced cost, high thermal conductivity, and robustness to thermal degradation. The system is tilted so when water condenses on the glass cover it drips on one side and can be collected. During the day, water is flown back inside the system (Figure 2 b). Due to the solar radiation and temperature differential between glass and insulating material, water in the air gap evaporates and condenses on the inner face of the glass (Gad, Hamed and El-Sharkawy, 2001).

Another category of simple fog collectors are radiative condensers (Figure 2 c), which exploit high emissivity properties of the surface material to foster quick cooling of the dew collecting surface during the night (Muselli *et al.*, 2002). The collecting surface can be made of different foil materials, as long as the materials used have high infrared (IR) emissivity. The most common additives applied to the foils to enhance emissivity are titanium dioxide (TiO_2) and barium sulphate ($BaSO_4$). High emissivity values imply that those surfaces are able to cool down relatively quickly during the night. To enhance the system cooling and condensing capabilities it is also possible to build such systems according to predominant wind directions, to avoid that evaporative phenomena affect the condenser yield (Beysens *et al.*, 2003). This kind of condenser can be easily built exploiting existing tilted roofs surfaces in rural areas, as suggested by Sharan et al. (2007).

We present a comparison of the main technical features characterizing the existing fog harvesting systems, to help determining which features are most advantageous for fog harvesting integration in building envelopes. Declared yields for a number of existing collectors are reported in Table 1. Data also includes geographic locations and relative humidity ranges measured during the monitoring period. RH range values were retrieved from the published references. When this data was not included in the publication, the reference year weather file was considered (data accessed from Energy Plus© simulation software). This is the case of collectors [5], [6] and [10].

Table 1. Summary of collectors considered in the study, with indication of location, RH value ranges and yield per square metre

Collector type	**Collector name**	**Location**	**Coordinates**	**RH ranges [%]**	**Yield [l/sqm/day]**
MESH	1 - LFC	Abha, Asir Saudi Arabia	18.21° N, 42.50° E	90-100(Suau, 2010)	4
	2 - SFC	Abha, Asir Saudi Arabia	18.21° N, 42.50° E	90-100(Cáceres *et al.*, 2007)	6
	3 - SFC	Abha, Asir Saudi Arabia	18.21° N, 42.50° E	90-100(Beysens *et al.*, 2003)	3.2
	4 - SFC	Coloso Chile	23.45° S, 70.28° W	80-100(Gad, Hamed and El-Sharkawy, 2001)	3.2
	5 - SFC	Big Sur, California	36.23° N, 121.75° W	80-90[1]	3
	6 - LFC	Lepelfontein, South Africa	31.05° S, 17.50° E	60-90[2]	4.6
CHEMICAL CONDENSER	7 - Chemical absorption	Dharan Saudi Arabia	26.32° N, 50.13° E	90-100(Abualhamayel and Gandhidasan, 1997; Muselli *et al.*, 2002; Olivier and de Rautenbach, 2002; Gandhidasan and Abualhamayel, 2005; Cáceres *et al.*, 2007; Fessehaye *et al.*, 2014)	1.6
	8 - Chemical absorption	Egypt (not spec.)	-	40-50(Batisha, 2015)	1.5
RADIATIVE CONDENSER	9 - Condenser	Kothara Kutch, India	23.13° N, 68.93° E	90-100(Muselli *et al.*, 2002)	6
	10 - Condenser	Corsica island, France	41.92° N, 8.73° E	60-90[3]	0.38

[1] Weather data file
[2] Weather data file
[3] Weather data file

Mesh fog collectors, both SFC and LFC, perform better than the other systems. Radiative condenser [10] has an extremely reduced yield. On the contrary, condenser [9] shows one amongst the highest water collection. However, as all of the fog collectors included in this analysis were located in different geographic areas and operated under different climatic conditions, it is not possible to rely on declared yields to infer what is the most efficient fog collection system.

The yield of a fog harvesting system is affected by several climatic factors, such as wind direction and speed, relative humidity and temperature (Fessehaye *et al.*, 2014; Holmes, Rivera and de la Jara, 2014). These are likely to affect all types of the presented collectors, but wind is particularly relevant in the case of SFC and LFC, as it affects the flow of humid air through the mesh, which needs to be maximized to achieve the declared collection yield (Rivera and Lopez-Garcia, 2015). It can also have an influence in the case of radiative condensers (Muselli *et al.*, 2002). Radiation intensity is an additional parameter that affects daytime functioning of chemical condensers (Gandhidasan and Abualhamayel, 2007).

3. **Fog harvesting integration on building envelope**

The integration of fog harvesting as an additional function of the building envelope is innovative, as existing systems are located in open air field in most of the analyzed cases (Gandhidasan and Abualhamayel, 2007). The cost of building such systems is an aspect that may have an influence over design choices. SFC and LFC are extremely affordable, around 150$ in the case of SFC. This amount is related to the cost of materials for an entire SFC setup (Gandhidasan and Abualhamayel, 2007). This is not surprising taking into account the quantity and type of materials involved, and the simplicity of the supporting structure. Chemical condensers are more complex and involve the construction of a frame to include all the constituting elements. Unfortunately, no data about the actual cost are provided by authors. Radiative condensers have a declared unitary cost of 70 $/sqm (Cáceres *et al.*, 2007). However, this value is quoted for a specific service lifetime span of 50 years for the supporting structure, but excludes condensing foil replacement, which is generally necessary every 16 months.

Maintenance requirements and risk of premature failure are important issues to consider when designing fog collectors. This especially applies to the possibility of integrating such components in a façade, where circumscribed malfunctioning can still globally affect the building. Mesh collectors have shown maintenance-related issues in areas characterized by strong winds that can cause the mesh to break, calling for immediate and total replacement (Abualhamayel and Gandhidasan, 1997). However, some studies have developed numerical models that can help designing collectors that are more resistant to wind loads, which benefit from a more efficient use of the mesh mechanical properties (Gad, Hamed and El-Sharkawy, 2001). Chemical condensers are very complex systems, where the failure of a single component is likely to affect the functioning of the whole device. No particular failure mechanisms have been reported but authors believe that the presence of desiccants and narrow gutters for water collection could eventually suffer from clogging after a long operation time. Radiative condensers reported foil breakage due to high wind loads, similar to what happens in the case of meshes (Sharan, Beysens and Milimouk-Melnytchouk, 2007). However, the cost of foil replacement is higher than mesh cost.

Despite the sparse nature of available data, the number of successful projects on fog harvesting 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.

7. Conclusions

We presented different fog collection systems based on documented case studies. A literature review on different technologies already available on the market was presented, outlining the main advantages and disadvantages of employing a specific device. Some laboratory-tested prototypes of new technologies were also presented.

Mesh collectors have proved to be efficient in high RH conditions, and showed yields ranging from 3 to 6 l/sqm*day. SFC and LFC are simple and inexpensive systems, but premature failure may occur during their service life calling for immediate replacement, due to the sail effect during intense gusts of wind. On the other hand, chemical absorbers are more complex and expensive devices. Both the protection glass located at the front of the frame and the robust frame structure make them stronger and more durable. However, these systems showed lower yields if compared to meshes, even though they performed at the same collection level in two different RH conditions. This was due to an improvement of the underlying technical system, which leads to an increase in collecting surface for the same front collector area. Overall, condensers did not produce any particularly relevant amount of water. For radiative systems, the significant volumes collected by the galvanized iron roof presented, even if in particularly favorable climatic conditions, gives confidence to conduct further research for fog harvesting on metal surfaces. First results of an experimental campaign conducted by the authors on radiative surfaces are presented in a separate paper.

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