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SCIENTIFIC DESIGN OF MULTILAYER FOG COLLECTORS

Musaddaq Azeem, M.Sc.

SUMMARY OF THE THESIS

Title of the thesis: Scientific Design of Multilayer Fog Collectors
Author: Musaddaq Azeem, M.Sc.
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Department: Department of Material Engineering
Supervisor: prof. Ing. Jakub Wiener, Ph.D.

Committee for defence of the dissertation:

Chairman: prof. Dr. Ing. Zdeněk Kůs	FT TUL, Department of Clothing
Vice-chairman: doc. Ing. Pavel Pokorný, Ph.D.	FT TUL, Department of Nonwoens nd nanofibrous Materials
prof. Ing. Luboš Hes, DrSc., Dr.h.c.	FT TUL, Department of Textile Evaluation
prof. RNDr. Jan Pícek, CSc.	FP TUL, Department of Applied Mathematics
prof. Ing. Tomáš Vít, Ph.D.	FS TUL, Department of Power Engineering Equipment
doc. Ing. Josef Dembický, Ph.D. (opponent)	businessman
doc. Ing. Petr Henyš, Ph.D. (opponent)	FM TUL, Institute of Novel Technologies and Applied Informatics
doc. Ing. Michal Petruš, Ph.D.	FS TUL, Department of the Design of Machine Elements and Mechanisms
Ing. Michal Černý, Ph.D.	University of Pardubice, Faculty of Chemical Technology

The dissertation is available at the Dean's Office FT TUL.

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ABSTRACT

The growing concerns over desertification have spurred research into technologies aimed at acquiring water from nontraditional sources such as dew, fog, and water vapor. Some of the most promising developments have focused on improving designs to collect water from fog. However, the absence of a shared framework to predict, measure, and compare the water collection efficiencies of new prototypes is becoming a major obstacle to progress in the field. We addressed this problem by providing a general theory to design efficient fog collectors as well as a concrete experimental protocol to furnish our theory with all the necessary parameters to quantify the effective water collection efficiency. We showed in particular that multilayer collectors are required for high fog collection efficiency and that all efficient designs are found within a narrow range of mesh porosity. We support our conclusions with measurements on simple multilayer harp collectors.

Surface wettability contributed a major role in fog harvesting. Hydrophilic surfaces offer fast nucleation, while hydrophobic surfaces provide the droplets rapid transportation. Many animals and plants in arid environments control this tradeoff by naturally coated biphilic surfaces with structural designed wettability. This patterned wettability gives a high affinity for fog collection. This mechanism aims to reduce the friction and pinning force of the fog droplets sliding down towards storage. The reason to replace the traditional Raschel mesh with a harp design is to capture the maximal fog by avoiding clogging. We also established an experimental part focus on the wettability (hydrophilicity and hydrophobicity) of vertical harp or fog collector element (FCE). The FCE treated with hydrophilic treatments exhibited adverse effects while hydrophobic coating slightly improved the collection rate. Moreover, we examined the contact angle hysteresis (CAH) of our prototypes to verify the wettability effect.

KEYWORDS: fluid mechanics, fog collector, harp design, porous media, water collection efficiency, hydrophilicity, hydrophobicity, fog harvesting, fog collector element

ABSTRAKT

Rostoucí obavy z rozšiřování pouští podnítily výzkum technologií zaměřených na získávání vody z netradičních zdrojů, jako je rosa, mlha a vodní pára. Některé z nejslibnějších projektů se zaměřují na zdokonalení konstrukcí pro získávání vody z mlhy. Hlavní překážkou pokroku v této oblasti se však stává neexistence společného rámce pro předvídání, měření a porovnávání účinnosti sběru vody u nových prototypů. Tento problém jsme řešili tím, že jsme navrhli obecnou teorii pro projektování účinných sběračů mlhy a také konkrétní experiment, který naši teorii vybavil všemi potřebnými parametry pro kvantifikaci efektivní účinnosti sběru vody. Ukázali jsme zejména, že pro vysokou účinnost sběru mlhy jsou nutné vícevrstvé kolektory a že všechny účinné konstrukce se nacházejí v úzkém rozmezí pórovitosti sítě. Naše závěry jsme podpořili měřeními na jednoduchých vícevrstvých harfových kolektorech.

Smáčivost povrchu hraje při sběru mlhy významnou roli. Hydrofilní povrchy nabízejí rychlou nukleaci, zatímco hydrofobní povrchy zajišťují rychlý transport kapek. Mnoho živočichů a rostlin v suchých prostředích tento kompromis řídí přirozeným pokrytím bifilních povrchů se strukturálně řízenou smáčivostí. Tato lokální smáčivost poskytuje vysokou afinitu ke sběru mlhy. Tento mechanismus má za cíl usnadnit transport kapiček mlhy klouzajících dolů směrem k úložišti. Důvodem nahrazení tradiční rašlové sítě harfovou konstrukcí je zachycení maximálního množství mlhy zamezením jejího „ucpávání“ vodou. Experimentálně byla realizována i část zaměřená na smáčivost (hydrofilnost a hydrofobnost) vertikální harfové struktury nebo mlhového sběrného prvku (FCE). Modifikace FCE hydrofilní úpravou vykazovalo zhoršený záchyt vody, zatímco hydrofobní úprava tento záchyt mírně zlepšila. Kromě toho jsme zkoumali hysterezi kontaktního úhlu (CAH) našich prototypů, abychom plně kvantifikovali smáčivost povrchu kolektoru.

KLÍČOVÁ SLOVA: mechanika tekutin, mlhový kolektor, harfová struktura, porézní médium, účinnost sběru vody, hydrofilnost, hydrofobnost, sběr mlhy, prvek mlhového kolektoru.

Table of Contents

1. Introduction	1
2. Purpose and Aim of the Study.....	1
3. Overview of the current state of the problem.....	2
4. Theory	3
4.1. Total Water Collection Efficiency (η_{tot}).....	3
4.2. Maximizing η_{tot}	6
4.3. Fluid Mechanics Prediction of A_{∞} / A	7
5. Research Methodology	9
5.1. Materials.....	9
5.2. Collector Design	9
5.2.1. Construction of prototypes	10
5.3. Measurement of Aerodynamic Collection Efficiency.....	11
5.3.1 Yield measurements	13
5.4. Wettability.....	13
5.4.1. Plasma treatment with DBD reactor	13
5.4.2. Silane treatment.....	14
5.4.3. Characterization	14
5.4.4. Fog generator	14
6. Results and Discussion.....	15
6.1. Optimal Design of Multilayer Fog Collectors	15
6.1.1. Efficiency of multilayer fog collector.....	17
5.2. Wettability of Vertical Harps for Fog Collection	25
6.2.1. Characterization	27
7. Conclusions and Future Work.....	31
8. References	32
9. List of papers published by the author.....	37
9.1. Publications in journals	37
9.2. Contribution in conference proceeding.....	38
9.3. Citations.....	38
Curriculum vitae	39
Brief description of the current expertise, research and scientific activities.....	40

1. Introduction

Many regions of the world experience chronic water shortages and the associated impacts on human health and economic growth [1]. This crisis has spurred research for novel technologies to exploit alternative water sources such as fog [2, 3], dew [4-6], and even water vapor [7], where the conditions are favorable, fog stands out as one of the most attractive water sources because fog water can be collected in large amounts without any input of energy [8-10]. Because of its appeal, fog collection has been studied intensively in recent years resulting in a large body of work focused on improving the efficiency of fog collectors [11-18]. Fog collection is usually achieved with fine meshes exposed to the incoming fog stream. The minuscule fog droplets intercepted by the threads accumulate until they reach a critical size at which point the force of gravity overcomes the surface tension forces and allows the drop to slide down the collector's surface to reach the gutter at its base.

The central design challenge for efficient fog collection is to accommodate two physical processes that have opposite requirements [19]. On the one hand, fog collecting meshes cannot be very dense or present a major obstacle to the flow of air otherwise the incoming fog stream will simply bypass the structure laterally. On the other hand, fog droplets can be intercepted only if they encounter a mesh element while they transit through the collector. Therefore, overly open meshes are poor collectors, just as meshes are too dense. A related issue for fog collectors is clogging of the mesh by the water droplets that have been captured thus making the collector less permeable to the incoming fog and reducing the overall water collection efficiency [11].

Material scientists have sought to alleviate the problem of clogging by making structural changes to the mesh such as using harp designs [17, 20] or hierarchical branched patterns [21, 22] instead of using the standard criss-crossing meshes that tend to hold water drops in place. Other material science contributions have explored modifications of the collecting surfaces to allow intercepted droplets to coalesce and move quickly under the action of gravity [23-25]. In particular, modifications of the contact angle hysteresis can reduce the critical size a drop needs to reach before it is freed from the mesh [11]. However, many of these possible improvements will have to be scaled to realistic sizes ($>1 \text{ m}^2$) and produced at a competitive price (less than USD 25 per m^2) [26] before they can be used in the field.

2. Purpose and Aim of the Study

The supply of pure water has become a social issue and it obliges the material scientists working mutually with functional ecological entities to bring novel fog collection techniques. An alternative avenue to improve the performance of fog collectors arises from observations of the bromeliad *Tillandsia landbeckii*, a plant that relies almost exclusively on fog to fulfill its water needs [27-29]. *Tillandsia* forms large stands on the fog-prone coast of the Atacama Desert of Chile. These stands are striking in that the plants self-organize into bands orthogonal to the flow of fog (Figure

1A), thus allowing each plant direct access to the fog stream. Moreover, the leaves and stems of *Tillandsia* are reduced to thin filamentous structures organized into a three-dimensional mesh, a unique feature among bromeliads (Figure 1B). Finally, a dense layer of hydrophilic trichomes covers the plant surfaces (Figure 1B). Three length scales emerge from observations of *Tillandsia*: the smallest length scale is that of the trichomes ($\sim 100 \mu\text{m}$) involved in intercepting fog droplets, the intermediate length scale is the characteristic pore size between the leaves ($\sim 1 \text{ mm}$) through which the fog stream must filter, the largest length scale is the self-organization of *Tillandsia* plants into fog collecting stands ($\geq 1 \text{ m}$). These observations indicate that 3-D structures, with appropriately selected length scales, can be efficient at collecting fog.

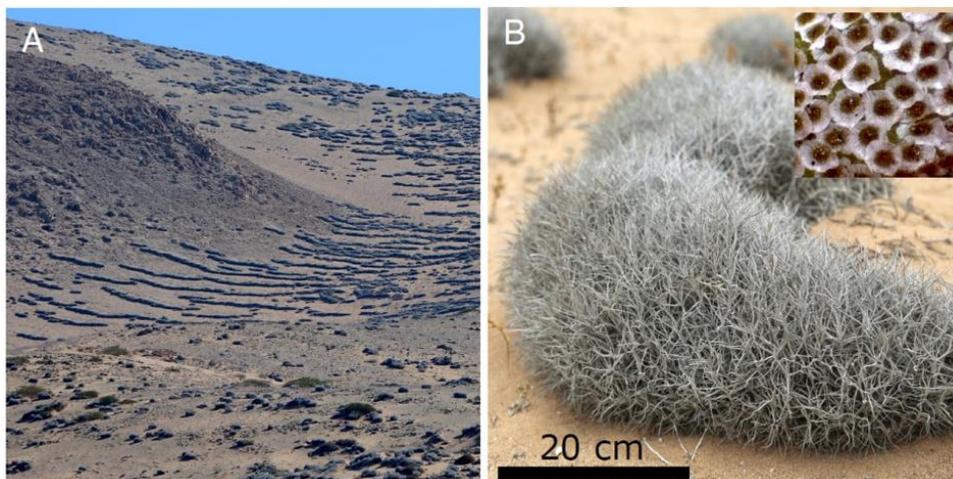


Figure 1: Aerodynamics of fog collection. (A) A stand of the bromeliad *Tillandsia landbeckii* in the Atacama Desert of Chile. (B) Close-up of *Tillandsia landbeckii* showing the dense three-dimensional array of leaves. Inset: the hydrophilic scale-like trichomes covering the leaves and branches of *Tillandsia*.

3. Overview of the current state of the problem

Inspired by *Tillandsia landbeckii*, we investigated the potential offered by multilayer designs for improving the water collection efficiency of fog collectors (Figure 2A-C). Such 3-D structures can resolve many of the issues associated with single-layer collectors, including clogging. Despite having been field-tested more than 50 years ago; [30] the performance of multilayer collectors have not been studied theoretically except for one recent study [31]. Specifically, it is still unclear whether broadly applicable design principles exist. Here, we formalize the fundamental tradeoff associated with the capture of fog with multilayer collectors and demonstrate that simple design rules can guarantee nearly optimal fog collection efficiency.

Ideally, the most favorable fog collector would harvest the maximum fog droplets to accomplish. Our objective in this study is to prove that the total efficiency of our fog collector relies on the design and geometry of the collector. Although, hydrophobicity also plays an important role to

enhance the efficiency of fog collectors. The tiny droplets of fog are deposited on the surface of the collector element and enlarge by coalesces of the neighboring droplets with an elongated shape. Thus the fusion of enlarged water droplets triggered a minute slide along with the collector element. Meanwhile, the gap is available for new incoming fog droplets to be deposited on the collector elements and fill the surface with large droplets. While sliding downward, all the droplets have been rolled down on their way towards the storage. The whole phenomenon from the birth of droplets to slipping down depends upon the surface repellent structure and design of the collector. These parameters lead to confirm that the design of geometry in addition to hydrophobicity is the most important variable to enhance efficiency even expose to severe environmental conditions. However, CAH mimics a vital role in the coating phenomena to predict the significance of applied material.

4. Theory

4.1. Total Water Collection Efficiency (η_{tot})

To formalize the performance of fog collectors, we define, as others have done before [19, 31, 32], the water collection efficiency (η_{tot}) as the water flux coming out of the collector's gutter (J , $\text{g} \cdot \text{s}^{-1} \cdot \text{m}^{-2}$) divided by the liquid water flux of the unperturbed fog upstream of the collector:

$$\eta_{tot} = \frac{J}{LWC \cdot u_{\infty}} \quad (1)$$

Where LWC is the liquid water content of fog and u_{∞} is the velocity of the unperturbed fog flow, which we assume to be orthogonal to the surface of the collector. A typical value of the LWC is $0.2 - 0.5 \text{ g} \cdot \text{m}^{-3}$ while the characteristic fog velocity is $2 - 5 \text{ m} \cdot \text{s}^{-1}$ [32, 33].

It is convenient to define η_{tot} in geometrical terms first by considering how a fog droplet upstream of the collector can ultimately be found in the flux of water " J " coming out of the collector's gutter. The first two stages of collection operate at different length scales (Figures 6B, C). First, we consider what happens at the scale of the entire fog collector (Figure 2C), where the characteristic Reynolds number based on collector size ($l \sim 1-10 \text{ m}$) and unperturbed air velocity ($u_{\infty} \sim 5 \text{ m} \cdot \text{s}^{-1}$) is

$$Re = \frac{u_{\infty} l}{\nu} \sim 10^6$$

Where ν is the kinematic viscosity of air. Incoming fog droplets are part of an airstream which must filter through the collector if the droplets are to be captured. Because the collector is an obstacle to the free flow of the airstream, a fraction of the incoming fog will simply bypass the collector (Figure 2A). The filtered fraction (φ) can be quantified geometrically as the ratio of two areas:

$$\varphi = \frac{A_{\infty}}{A},$$

Where A_{∞} is the area for the unperturbed incoming fog flow that will filter through the collector of frontal area A . In the specific case of a square collector (Figure 2A, B), the filtered fraction is

$$\phi = \left(\frac{l_\infty}{l}\right)^2$$

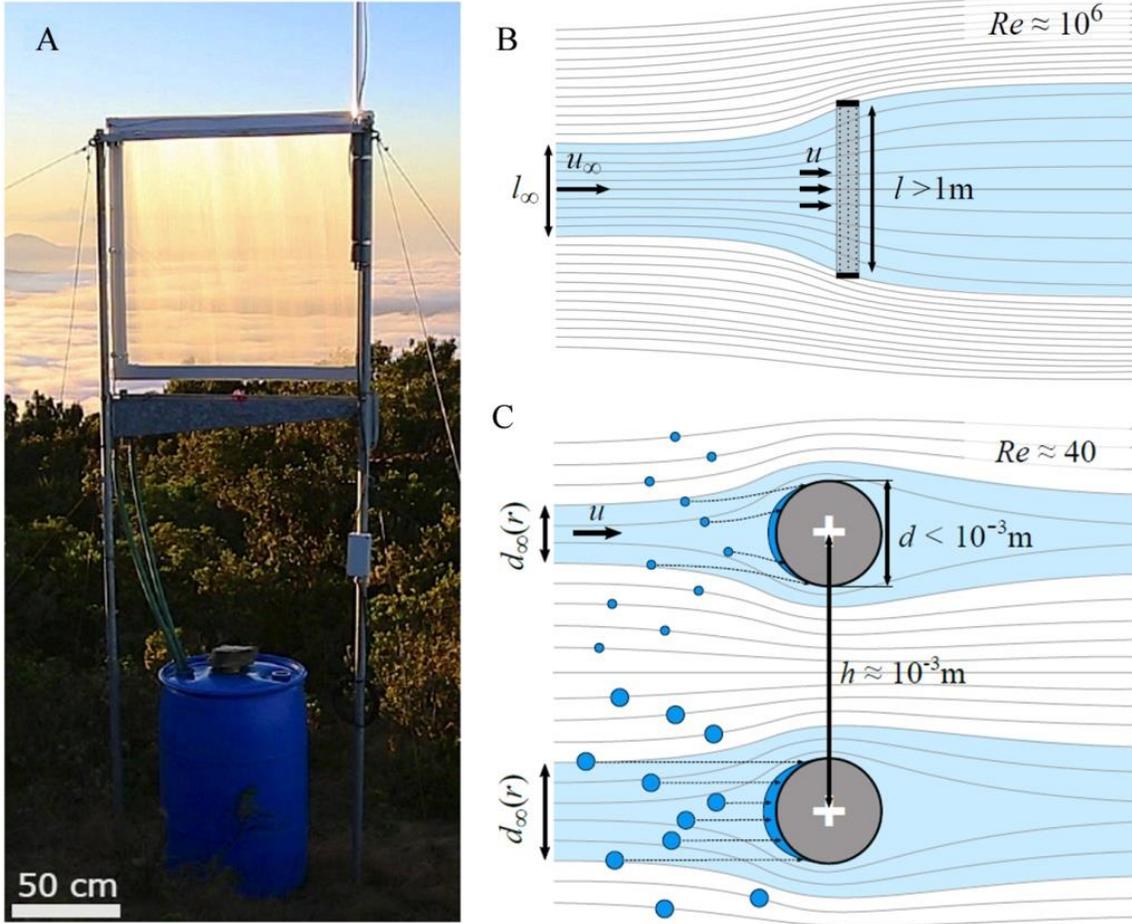


Figure 2: (A) Prototype of a 1 m \times 1 m multiharp fog collector with a mesh solidity $s = 0.3$ per layer and $N = 4$ layers. (B) Top view of the air flow around a fog collector. The typical collector length is $1\text{ m} \leq l \leq 10\text{ m}$. Streamlines are drawn based on wind tunnel experiments by Ito and Garry [34], with square mesh gauze of solidity 0.63 at $Re \approx 10^6$ based on the collector size. (C) Close-up of the air flow around the section of two cylindrical threads of the collector. The diameter of the threads $d \approx 150 - 160 \mu\text{m}$ for the collector is shown in (B) and the experiments discussed below. $d_\infty(r)$ represents the span of streamlines whose droplets will be intercepted by the thread directly downstream. The top and bottom halves of the diagram show the interception of the small and large droplets, respectively; dashed lines indicate approximate trajectories of intercepted droplets. Streamlines are based on Gordon's simulations [35] at $Re = 20$ based on the thread diameter.

The second collection stage takes place at a microscopic scale and pertains to the droplets transiting through the collector. Of these filtered droplets, only a subset will be on a trajectory that ensures collision with one of the collector elements (Figure 2C). For any given layer of the collector, the probability that a droplet collides with a thread is given by $\frac{d_\infty(r)}{d} s$, where the ratio $\frac{d_\infty(r)}{d}$ represents the efficiency of inertial impaction for a droplet of radius r (Figure 2C) and s is the solid fraction,

or solidity, of the layer ($s = d/h$ for our harp design). Conversely, the probability that a droplet captured by a layer has a radius in the interval $[a, b]$ is

$$s \int_a^b \frac{d_{\infty}(r)}{d} f(r) dr \quad (2)$$

where $f(r)$ is the probability density function for droplet sizes.

Given that the mass of water provided by a droplet scales with r^3 , the relative contribution of droplets to the capture efficiency is

$$s \int_a^b \frac{d_{\infty}(r)}{d} m(r) dr, \quad (3)$$

Where

$$\int_a^b m(r) dr \approx \left(\frac{\int_a^b r^3 f(r) dr}{\int_0^{\infty} r^3 f(r) dr} \right) \quad (4)$$

$\int_a^b m(r) dr$ is the mass fraction of liquid water contained in droplets with radius in the interval $[a, b]$ [36].

Finally, to these two processes, we should add the drainage efficiency (η_{drain}) [19, 31]. The drainage efficiency represents the fraction of the intercepted volume of water that ultimately reaches the tank of the collector. The drainage efficiency may be reduced by re-entrainment of captured droplets under high wind conditions [37] and potential leaks in the gutter and pipe leading to the collector's tank.

In the case of a single-layer collector, the three processes detailed above lead to the following total water collection efficiency:

$$\begin{aligned} \eta_{tot} &= \eta_{AC} \eta_{capt} \eta_{drain} \\ &= \underbrace{\left[\frac{A_{\infty} s}{A} \right]}_{\eta_{AC}} \underbrace{\left[\int_0^{\infty} \frac{d_{\infty}(r)}{d} m(r) dr \right]}_{\eta_{capt}} \eta_{drain} \end{aligned} \quad (5)$$

Where η_{AC} is the Aerodynamic Collection Efficiency (ACE) introduced by Rivera [19]. When considering a collector with N layers, the total collection efficiency takes the form:

$$\eta_{tot} = \frac{A_{\infty}}{A} \left[1 - \underbrace{\int_0^{\infty} \left(1 - \frac{d_{\infty}(r)}{d} s \right)^N m(r) dr}_{\text{lost mass fraction}} \right] \eta_{drain} \quad (6)$$

where the term $\left(1 - \frac{d_{\infty}(r)}{d} s \right)^N$ is the probability that a drop of radius r traverses the N layers of the collector without being intercepted. Consequently, the integral represents the mass fraction of liquid water that filtered through the collector without being intercepted.

Three tacit assumptions were made to arrive at Eq. (6). These assumptions are listed here in order to define clearly the range of validity of our result. First, we assumed that the incoming airflow

both far-field and just upstream of the collector is orthogonal to the collector's surface. We justify this assumption because; the optimum fog collectors are quite porous, with approximately ~80% of the incoming fog flow passing through the collector. In this regime, the air velocity has a negligible component tangential to the collector surface, so the interaction of the airflow with the collector filaments does not depend on the position within the collector. Second, we assume that $\frac{d_\infty(r)}{d}$ is constant at all locations within the collector. This assumption implies a uniform mesh such as the harps under consideration but would have to be modified for meshes made of intersecting weft and warp threads and potentially differing in their size and shape. Third, in deriving the lost mass fraction, we make the hypothesis that the distance between the layers is sufficiently large to allow the fog stream to regain uniformity before reaching the next layer. As we will show below, the optimal interlayer spacing ranges between 6 and 9 mm, which is at least 40 times greater than the characteristic thickness of the layers in our prototypes.

4.2. Maximizing η_{tot}

Because Eqs. (5) and (6) are geometrical definitions of η_{tot} , they are valid irrespective of the fluid mechanics model that might be developed to quantify the collection efficiency. Ideally, we would like to design the collector such that all steps in the collection of fog droplets are maximized to achieve a total water collection efficiency approaching unity. Our goal in this section is to demonstrate that η_{AC} is the only component of η_{tot} that involves some fundamental design tradeoff.

We begin with the drainage efficiency η_{drain} which is included in Eqs. (5) and (6) to take into account the possibility that captured fog droplets are re-entrained by the airstream or otherwise lost due to leaks in the system. Although leaks need to be considered carefully in any implementation of a fog collector, they are outside the scope of a fluid mechanics analysis. Re-entrainment needs to be considered more carefully.

Two ways to eliminate re-entrainment are (*i*) the use of multi-layer collectors to allow re-entrained drops to be re-captured by a layer farther downstream [30] and (*i i*) the reduction in the size of the drops clinging to the collector surface so that the drag on these drops does not exceed the critical value that would cause them to detach. These design requirements are in fact among those put forward to optimize the other aspects of the collection process; therefore the drainage efficiency will be optimized *de facto*. In what follows, we set $\eta_{drain} = 1$ and focus on the other terms of Eqs. (5) and (6).

At the operational *Re* number of fog collectors, the ratio $\frac{d_\infty(r)}{d}$ reflects a deposition mechanism by inertial impaction [20]. For a droplet of radius r , the efficiency of the impaction mechanism follows the relation [20, 38]:

$$\frac{d_\infty(r)}{d} = \frac{Stk}{Stk + \pi/2} \quad (7)$$

Where $Stk = \frac{2\rho_\omega r^2 u}{9\mu d}$ is the Stokes number, ρ_ω is the density of the liquid, u is the velocity of the air stream, μ is the dynamic viscosity of air, and d is the diameter of the thread. This efficiency increases with increasing *Stk*; however, we note from the definition of *Stk* that the thread diameter

" d " is the only parameter that can be tuned in the context of a passive fog collector. Because Stk increases for decreasing d , the width of the elements on which droplets are impacted should be reduced to a minimum. More precisely, Labbé and coworkers [20] demonstrated that the size to be considered is the diameter of the thread with the water film or drops covering it. The reduction in the size of the collecting elements can be done at constant solidity and without compromising other steps of the fog collection process.

Consequently, the geometrical ratio $\frac{d_\infty(r)}{d}$ can be made as close to unity as one desires, although maximizing $\frac{d_\infty(r)}{d}$ for all droplets, size classes are unwarranted since the smallest droplets are the most challenging to capture, and yet they represent a vanishingly small fraction of the total LWC of fog [33].

In what follows, we consider a small operating size for the collecting elements so that $d_\infty \rightarrow d$. In this limit, Eq. (6) becomes:

$$\lim_{d_\infty \rightarrow d} \eta_{tot} = \eta_{AC} = \underbrace{\left[\frac{A_\infty}{A} \right]}_{\varphi} \underbrace{[(1 - (1 - s)^N)]}_{\chi} \quad (8)$$

This equation captures in its most general form the Aerodynamic Collection Efficiency (η_{AC}); that is, the fraction of droplets in an unperturbed upstream flow of area A that are both filtered by (φ), and incident to (χ), the elements of a multi-layer collector.

The ACE is of special significance because it encapsulates the fundamental trade-off in the design of efficient fog collectors. While the incident fraction χ increases with increasing solidity s and the increasing number of layers N , the same parameter changes reduce the collector porosity and therefore decrease the filtered fraction φ .

4.3. Fluid Mechanics Prediction of A_∞ / A

Determining ACE for a specific collector involves finding the ratio $\varphi = \frac{A_\infty}{A}$ using the design parameters of the collector, such as the solid fraction of the individual mesh layers and the total number of layers. We first note that incompressibility of the flow together with mass conservation imply $Au = A_\infty u_\infty$ (Figure 2B). Therefore, the geometrical definition of the filtered fraction is also a statement about the ratio between the mean velocity across the collector mesh and the velocity far upstream of the collector, that is:

$$\varphi = \frac{A_\infty}{A} = \frac{u}{u_\infty} \quad (9)$$

We follow the many earlier studies of fluid flow through and around porous structures that equate to two alternative definitions of the pressure drop across the porous material, the first one at the scale of the porous medium and the second one at the scale of the far-field flow. At the microscopic scale, the pressure drop is

$$\Delta P = k \frac{\rho_{air} u^2}{2} \quad (10)$$

where ρ_{air} is the density of air and k is the pressure drop coefficient for the flow of an inviscid fluid through a porous medium. This equation arises naturally from Bernouilli's principle [36]. As we shall see, since " k " is typically not constant over a very large range of velocities, the pressure drop coefficient is necessarily expressed in terms of the solid fraction of the medium and the Reynolds number. At the scale of the entire collector, the pressure drop across the mesh is also related to the drag coefficient C_D ,

$$\Delta P = \frac{F_D}{A} = C_D \frac{1}{2} \rho_{air} u_{\infty}^2 \quad (11)$$

because the drag force F_D per unit area on the screen must equal the pressure drop. Eq. 11 represents the so-called "form drag" and is valid for blunt objects at high Reynolds numbers, which is the case for fog collectors [39]. Equating the two pressure drops we obtain the filtered fraction

$$\varphi = \frac{A_{\infty}}{A} = \frac{u}{u_{\infty}} = \sqrt{\frac{C_D}{k}} \quad (12)$$

This equation has been used in its various forms by Taylor [40], Koo and James [41], Steiros and Hultmark [42] among many others.

There is no consensus on how to express the drag coefficient C_D and the pressure drop coefficient (k) in terms of the design parameters of the collector mesh. To our knowledge, the most recent and most complete treatment is due to Steiros and Hultmark [42] (later termed Steiros 2018); who extended the earlier work of Koo and James [41] by including the so-called "base-suction" and thus obtained accurate predictions of the drag coefficient over the entire range of solid fractions. According to their model, the drag and pressure drop coefficients are

$$C_D = \frac{4}{3} \frac{(1-\varphi)(2+\varphi)}{(2-\varphi)} \quad (13)$$

$$k = \left(\frac{1}{(1-s)^2} - 1 \right) - \frac{4}{3} \frac{(1-\varphi)^3}{\varphi^2(2-\varphi)^2} \quad (14)$$

Substitution of these two relations in Eq. 12 gives an implicit relation for the filtered fraction as a function of the solidity. Finally, since k is the coefficient for the pressure drop across one layer of the collector, a conservative estimate for the total pressure drop across multiple layers is obtained by multiplying k by the number of layers in the collector. The additivity of the pressure drop coefficient was confirmed by Eckert and Pflüger [43] when the distance between the screens is sufficiently large. Idel'Cik estimates that the pressure drop across multiple layers is additive as long as the distance of separation between the layers exceeds 15 times the size of the threads (Idel'Cik, [44] page 291).

5. Research Methodology

This research part includes the materials and methodology for the development of an efficient fog collector. The optimal design of multilayer fog collector and the effect of wettability have been discussed experimentally and theoretically.

5.1. Materials

Cotton spun yarn, polyester, polypropylene, and polyethylene were used to initiate the experiments for the best possible selection. Cotton ring spun yarn was collected from the KMI lab, TUL while all the polymers were obtained from the Hahl Filaments GmbH, Munderkingen, Germany.

Table 1: specification of all the materials used for the study

Material	Color	Diameter (mm)	Density (g/cm ³)
Cotton Spun Yarn	Black	0.16	1.54
PES monofilament	Transparent	0.15	1.39
PE monofilament		0.15	0.95
PP monofilament		0.15	0.92

Various systems are being used to measure the yarn diameter in the textile industry but here we mentioned the diameter in millimeters (mm). Laboratory microscope was used to measure the diameter. PE monofilament was used to exercise the experiential part due to its favorable properties e.g. weather resistance, low water absorbency, recyclable, biodegradable, cheap, and easily available [45].

5.2. Collector Design

Raschel Mesh was obtained from the bioengineering laboratory, Universidad Adolfo Ibáñez-Campus Viña del Mar, Chile. The design of the mesh is much porous so double layer is used for fog collection. The ribbon-like structure and high porosity of the mesh was considered the major drawback to collect a high yield of fog water as shown in figure 3 (A, B).

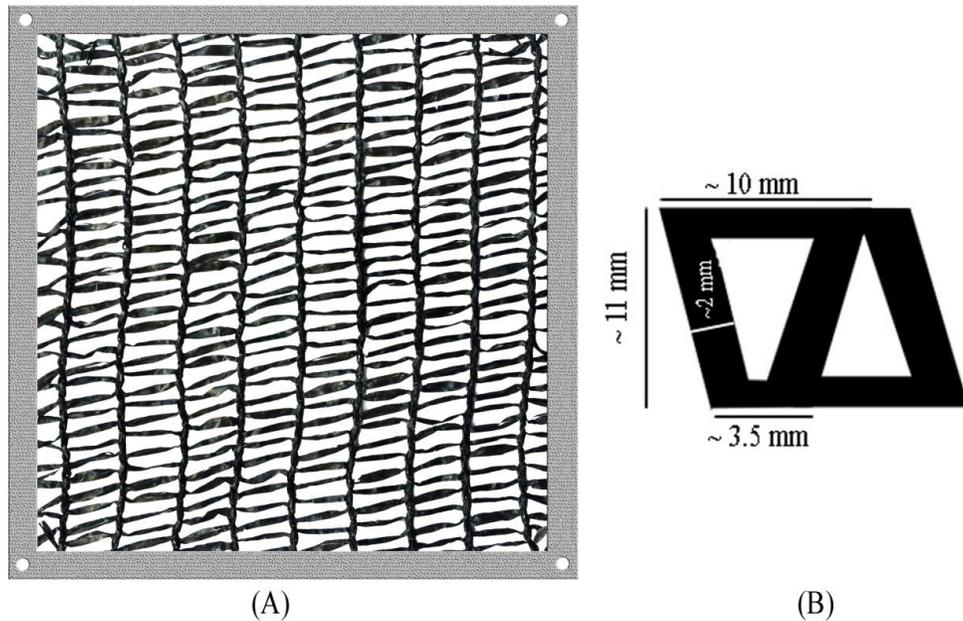


Figure 3: Knitting pattern Raschel mesh. (A) Prototype 100 mm×100 mm. (B) Structure of mesh

5.2.1. Construction of prototypes

Multi-layered collectors were built using fast prototyping tools. Square plexiglass frames with a 100 mm × 100 mm central open area were cut using a laser cutter (Ready Cut) as used in Figures 3A and 4A. Evenly spaced notches (typical spacing: $1 \text{ mm} \leq h \leq 2 \text{ mm}$) were made in the upper and lower edges of the frame to hold polyethylene monofilaments ($d = 150\text{-}160 \text{ }\mu\text{m}$) into a vertical harp arrangement (see figure 9).

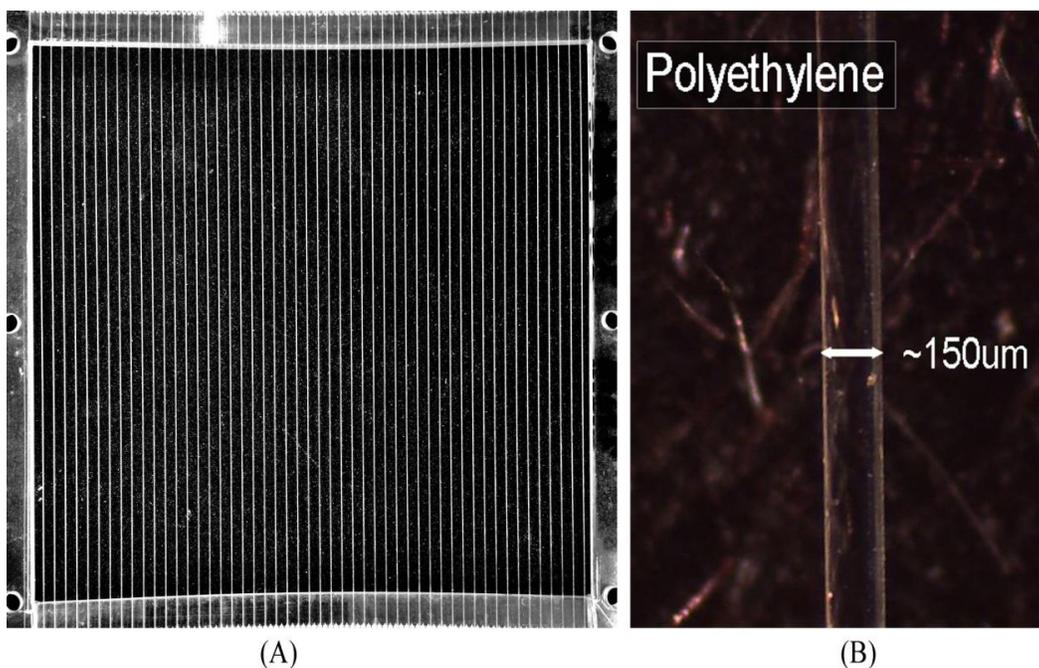


Figure 4: Harp collector built with PE monofilament. (A) Prototype 100 mm × 100 mm. (B) microscopic view of PE monofilament

These frames were then stacked with different inter-layer spacing to form a multilayer fog collector. The experiments reported here were done with a staggered relative alignment between successive layers. All the trials with staggered and in-line arrangements of layers were measured to fix it for the rest of the experiments. Note, however, that the staggered or in-line arrangements of layers had no significant effect on the performance of the collector. Figure 11 illustrated in the results confirm the verdict.

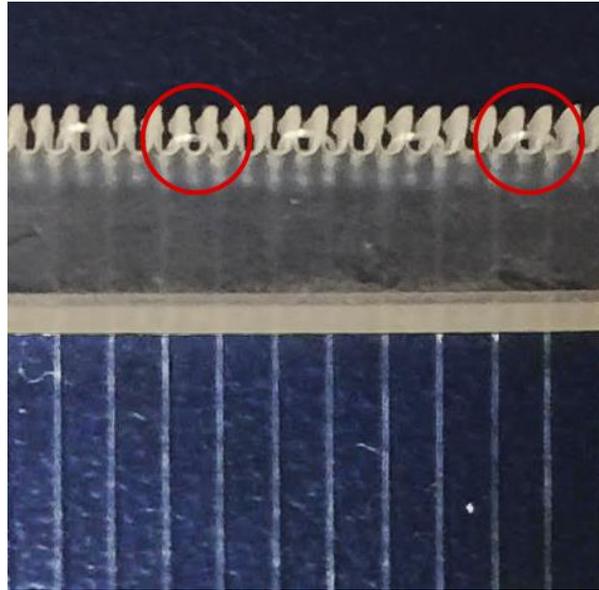


Figure 5: Construction of harp collector with evenly spaced notches

5.3. Measurement of Aerodynamic Collection Efficiency

Flow experiments were performed with an open-jet wind tunnel developed specifically to measure the efficiency of fog collector prototypes under natural conditions. The tunnel consists of two elements: a lower nebulization chamber for fog production and an upper flow chamber to accelerate the fog cloud and guide it into a uniform jet (Figure 6). The nebulization chamber contained ~50 L of water within which was immersed a 300 W 12-head ultrasonic nebulizer (Model DK12-36). The fog produced in this chamber was injected into the upper chamber by a 16 W, 200 mm × 200 mm ventilation fan. Within the flow chamber, an array of 16, 80 mm × 80 mm, computer fans accelerated the fog toward a contraction that converged the fog stream to a jet of 140 mm × 140 mm in cross-section.

Both the ventilation fan and the array of computer fans were powered through variable voltage transformers allowing us to set the jet velocity in the range 0.1 – 4.2 m s⁻¹. A honeycomb filter was placed at the upstream end of the contraction to eliminate turbulence and provide a homogeneous fog flow.

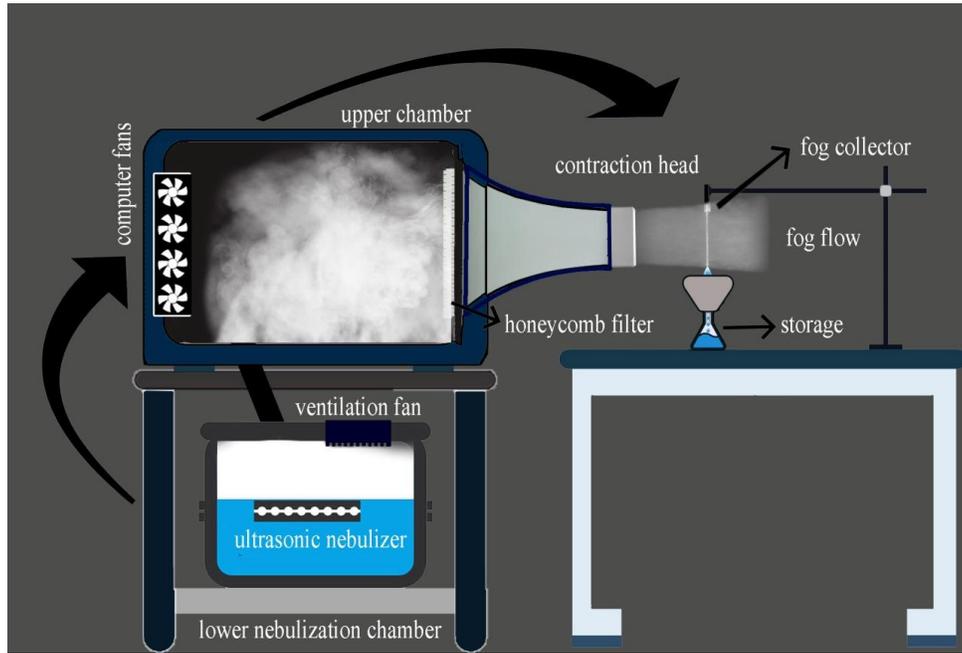


Figure 6: Flow diagram of the platforms to quantify the two stages of fog droplet collection.

The flow of fog through and around the collector prototypes was visualized by using a Phantom V611 high-speed camera equipped with a Canon EF 100–400 mm telephoto zoom. Images were acquired at a rate of 4000 fps (exp $240 \mu\text{s}$) with a camera resolution of 1024×768 pixels and an image scale of $270 \mu\text{m}/\text{pixel}$. Analysis of the flow pattern was performed using a Matlab program first developed by Dr. A. F. Forughi at the University of British Columbia (Vancouver, Canada) and made freely available on Github (<https://github.com/forughi/PIV>).

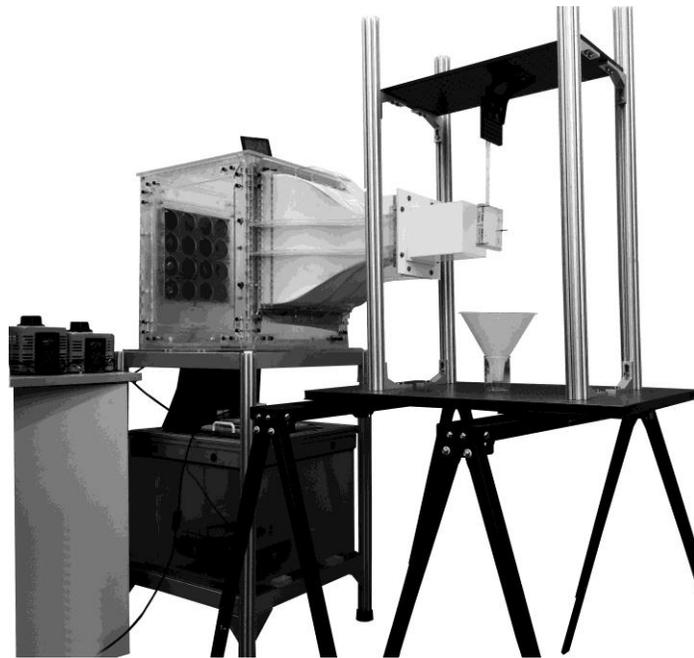


Figure 7: Wind tunnel platform used to measure the large scale flow field.

5.3.1 Yield measurements

To measure the yield, the prototypes were hung at a distance of 100 mm from the opening of a wind tunnel equipped with a fog chamber (see Figures 7 and 8A). The higher distance between the opening of a tunnel and prototype results in stray of fog fraction while lower distance could generate pressure inside the wind tunnel. The water collection rate was found slightly higher when the distance between the opening of a wind tunnel and prototype was 100 mm as shown in figure 8B. The water was collected in a funnel leading to a graduated cylinder. Collection occurred over a total time interval of 15 minutes following an initial saturation period of 5 minutes.

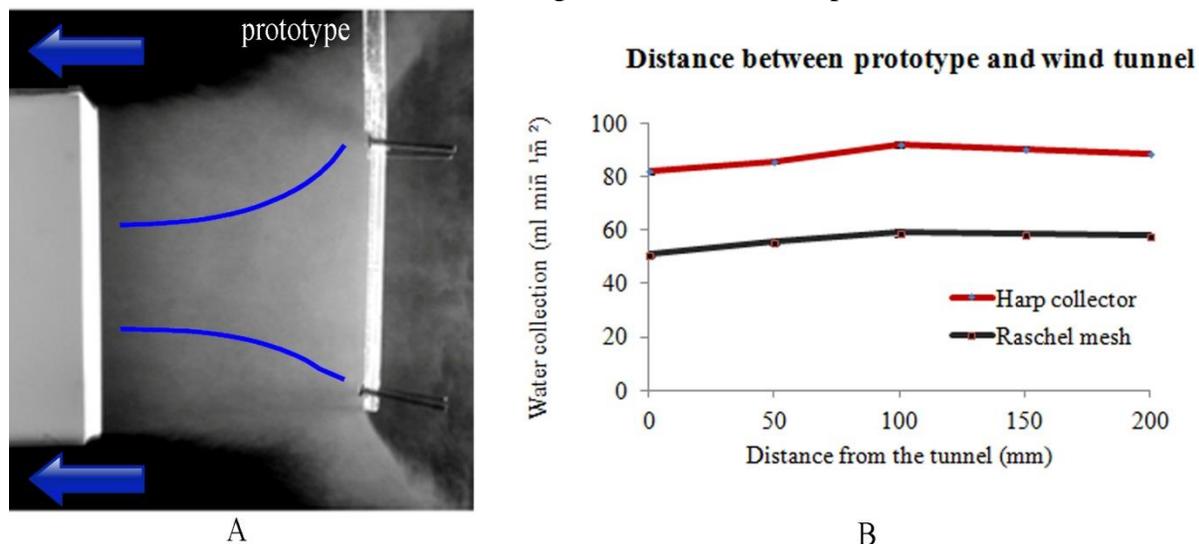


Figure 8: Measurement of the yield. (A) The prototypes from the opening of a wind tunnel. (B) Optimized the distance between wind tunnel and prototype

5.4. Wettability

The chemical structure of PE consists of straight carbon-hydrogen chains, thus permitting diverse surface modifications. The PE monofilaments of diameter 150 μm were acquired from HAHN Filaments Company, Germany. Some samples were processed for hydrophilicity and exposed to dielectric barrier discharge (DBD) plasma. Some samples were experimented with for hydrophobicity and exposed to silane treatment. For a better comprehension of the methods linked with adhesion at the interface, a systematic study of surface properties, both physical and chemical is very important. Herein, the main purpose of wettability is to enhance the efficiency of the fog collector and avoid clogging along with the minimum pinning force. Moreover, fog collectors with high droplet capture efficiency have a high rate of water accumulation and retention. Such fog collectors are not favorable for fog water harvesting.

5.4.1. Plasma treatment with DBD reactor

Plasma treatments were performed on PE monofilament with a parallel-plate DBD-system at medium pressure. The reactor consists of two copper electrodes (upper and lower electrodes) covered with glass plates. A monofilament sample was placed onto the lower electrode to achieve

a reproducible discharge gas composition for 5 minutes. For DBD plasma discharges three different samples were prepared with dry air treatments. A vast range of literature reviews has been reported that the plasma-treated polyethylene fibers with different gasses are used to enhance the energy absorption and interfacial shear strength [46, 47].

5.4.2. Silane treatment

In our experiments, silanization of monofilament PE was performed with dichlorodimethylsilane. For this purpose, silane 10 g/l was applied to the fabric under the pad-dry-cure method. 3 dips were performed and the time of each dip was 1 min. The drying temperature was 70 °C and the curing process was done to fix the silane. After that, hydrophobic performance was evaluated by contact angle measurement.

5.4.3. Characterization

Surface topography was characterized by XE-70 Atomic Force Microscope (AFM) system (Park Systems™, Suwon, South Korea). The static contact angle was measured by using Krüss Easy Drop optical system (Hamburg, Germany). A 0.5 microliter water droplet was used to compute the contact angles automatically within 3s using the Laplace-Young curve-fitting procedure. The dynamic contact angle was performed by growing the volume of the droplet on the FCE from 0.5 µl to 1 µl. CAH was measured from the advancing and receding contact angles. All of these calculations were taken at room temperature. Computer software ImageJ was used to measure the CAH.

5.4.4. Fog generator

To measure the yield of fog water collection, the samples of treated and untreated monofilaments were hung with vertical stand at room temperature and 100% humidity as illustrated in Figure 9. The TWIN-humidifier (Brno, Czechia) was utilized to generate fog with a velocity of 4-4.5 m/s. The aerosol particle size or mass median diameter (MMD) was approximately 5 micrometers. The hanging specimens were exposed to a fog stream for 30 minutes and then measured the yield of collected fog droplets.

Table 2: Properties of TWIN-humidifier

Model	Voltage (V)	Frequency (Hz)	Watt (W)	Flow rate (mm/mint.)	Particle size (µm)
SPS-702	220-240	50	30	0.4	5



Figure 9. The diagram of the experimental setup for fog collection.

6. Results and Discussion

The study consists of two major parts; the first is about the optimal design of multilayer fog collectors and the second part is about the surface wettability of vertical harps for fog collection. The first part was started with four different materials (threads) to construct the fog collector. Cotton yarn was compared with other filaments (PES, PP, and PE) and found that spun yarn is not suitable for the study due to water retention in the structure as shown in figure 10. Polyethylene monofilament was selected for the rest of the study due to its versatile properties and highly reported in the previous study.

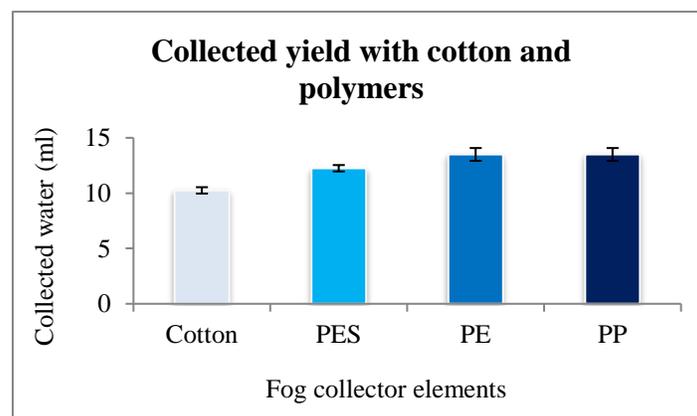


Figure 10: Yield collected of four different collector elements after 15 minutes with one layer

6.1. Optimal Design of Multilayer Fog Collectors

We designed a wind tunnel and optimized some of the variables to execute the experiments. We optimized the distance between two adjacent fog collector elements and the distance between wind tunnel and prototype as shown in figure 6 and figure 8.

For the control parameters, we also fixed the multilayer arrangement in the prototype. Figure 11A illustrated that the stagger and in-line arrangements of the harp are not affecting the total yield collection when using multilayer. Figures 11B and C visualized the in-line and stagger arrangements of layers in a multilayer fog collector.

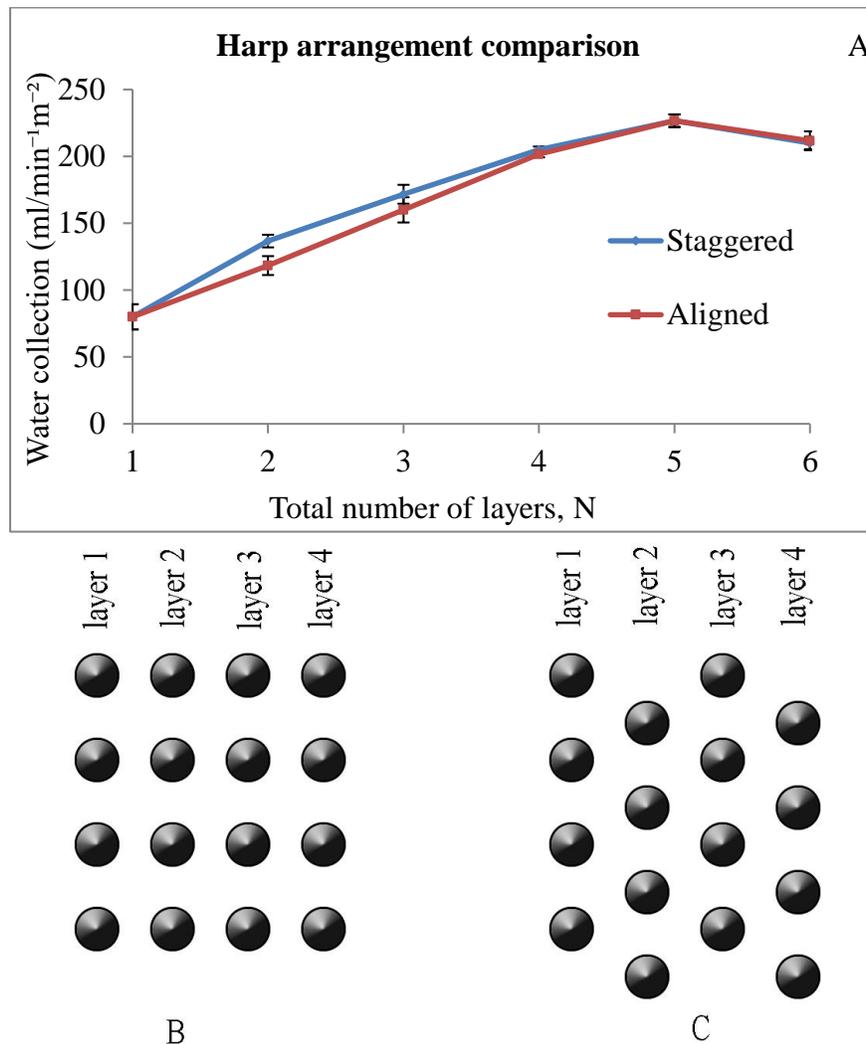


Figure 11: (A) Multilayer arrangement comparison. (B) In-line arrangements of layers. (C) Stagger arrangements of layers.

To optimize the distance between the two layers of fog collection it was set a series of experiments by varying the distance. Fourteen sets of experiments were performed by adjusting the space 0-36 mm between the adjacent layers. The interlayer spacing of 6 mm was found best to get maximum yield and allow the fog flow to be homogenous for striking the next layer as shown in figure 12.

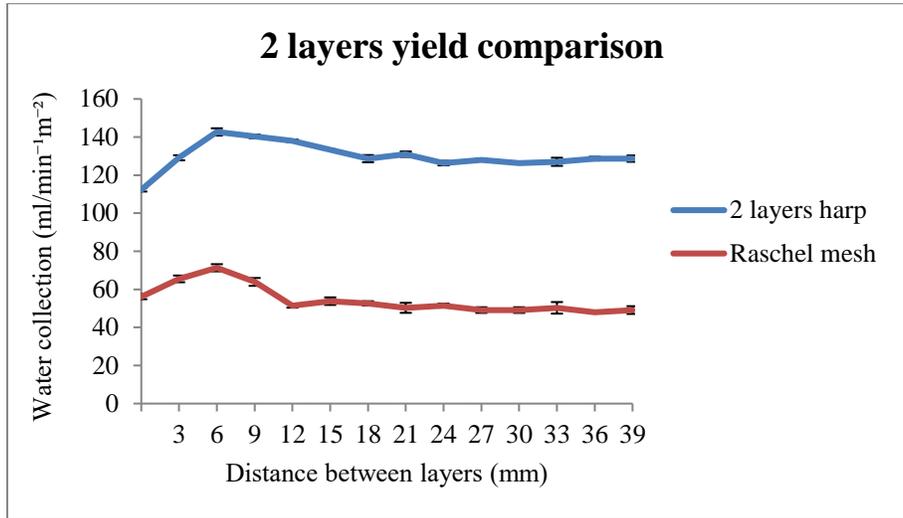


Figure 12: Effect of interlayer spacing on the yield of multilayer collectors.

6.1.1. Efficiency of multilayer fog collector

To maximize the overall collection efficiency, we must seek a high filtered fraction (φ) and a high incident fraction (χ). However, these quantities are maximized at opposite ranges of the parameters s and N (Figures 13A, B); this fact constitutes the central trade-off of fog collection. The results obtained in the previous section allow us to calculate the maximum ACE found at some intermediate values of these parameters.

As can be noted in Figure 13B, the incident fraction depends very nonlinearly on N which, at a single glance, establishes the notable advantage offered by multilayer designs. In a single-layer collector, the incident fraction cannot be maximized to unity, as this would imply complete obstruction of the mesh and thus no airflow through the collector. The use of several layers decouples, at least partially, the fluid mechanical processes behind the filtered fraction and the incident fraction. It is therefore possible to design the collector such that nearly all upstream droplets are on a collision course with one of the collector elements while maintaining the solidity significantly below unity (Figure 14B).

Even for a relatively modest 5-layer collector, a solidity as low as 0.5 can already guarantee a near maximal incident fraction (Figure 13B). The possibility of greatly increasing the incident fraction for intermediate solid fractions is the reason why multilayer collectors can be much more efficient. Moreover, because the equation for the incident fraction is purely geometrical, there is no doubt about the general validity of this conclusion.

Computation of the aerodynamic collection efficiency $\eta_{AC} = \chi\varphi$ for a broad parameter range indicates that it reaches a maximum of 49% for $N = 10$ (Figure 14). In contrast, single-layer collectors are confined to the line $N = 1$ and can reach a maximal ACE of only 30% at an operational solidity slightly above 0.5.

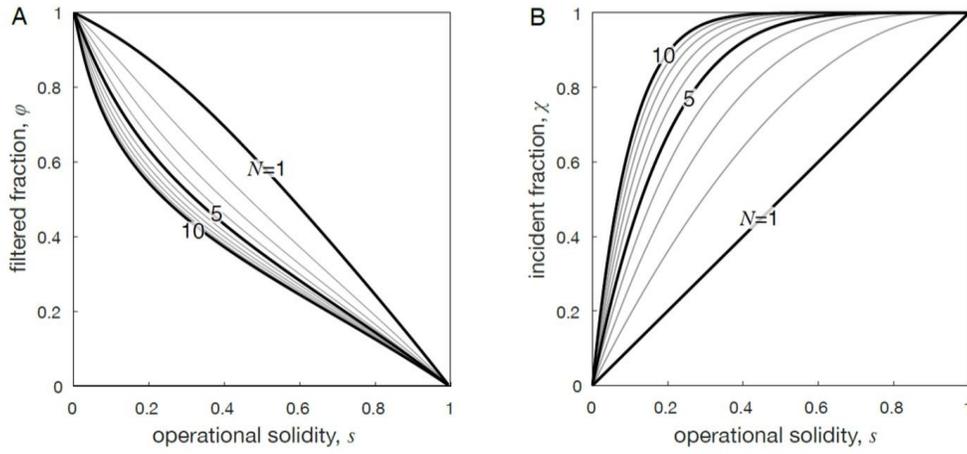


Figure 13: Aerodynamic collection efficiency for multi-layer fog collectors. (A) Filtered fraction predicted from the Steiros2018 model (Eqs. 12-14). (B) The incident fraction computed from geometrical considerations (Eq. 8, second term on the RHS).

Increasing the number of layers beyond 10 increases the ACE further; with the theoretical possibility of reaching an ACE of unity for a very large N (Figure 15). This limiting behavior raises the question of how many layers should be used in practice.

An answer emerges when considering the contribution to the total ACE made by each new layer (Figure 15). Beyond $N = 5$, the relative increase in ACE becomes vanishingly small. Therefore, considerations about the most efficient use of available materials would suggest that the number of layers should be limited to ~ 5 , at least in the limit where $d_\infty \rightarrow d$.

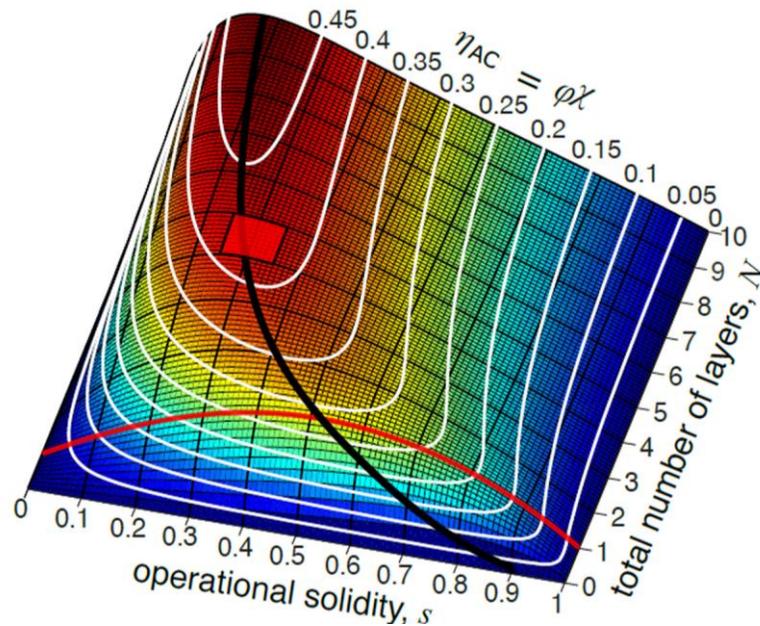


Figure 14: The ACE Ridge - a 3D representation of ACE as a function of the two control parameters s and N . A maximum ACE of 0.49 is observed for 10 layers, each with an operating

solidity of 0.17. Single-layer collectors are confined to the line $N = 1$ and have an ACE below 0.3. (Note: we have treated N as a continuous variable for illustration).

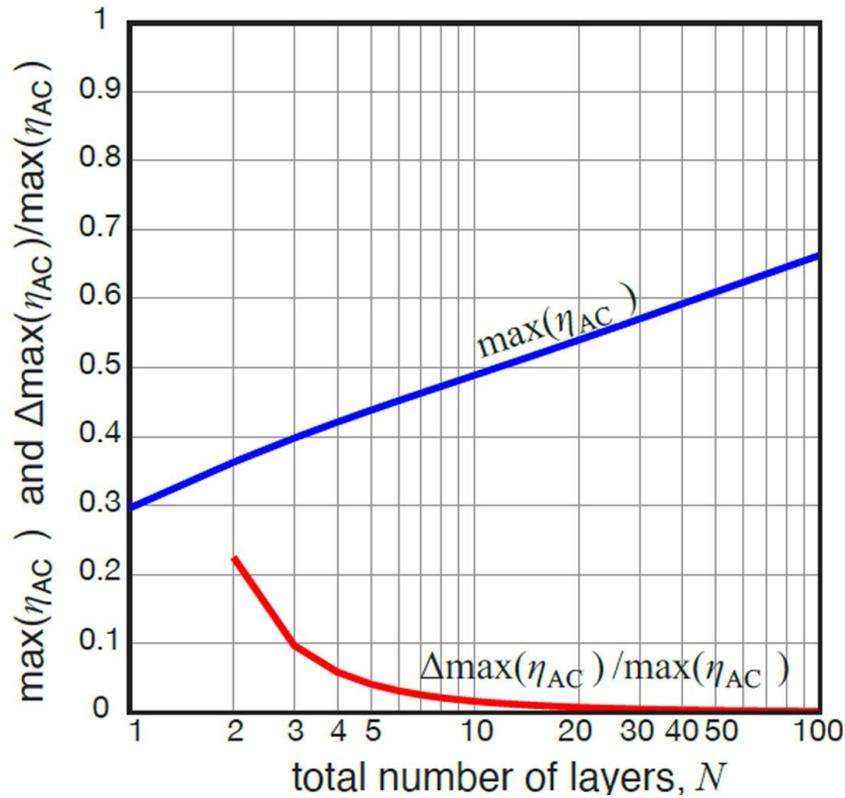


Figure 15: The maximal ACE as a function of N (plotted on a log scale). Although $\max(\eta_{AC})$ increases with increasing N , the relative ACE increase, $\Delta \max(\eta_{AC}) / \max(\eta_{AC})$, becomes small for $N > 5$ and negligible for $N > 10$.

As indicated in the theory section, the Steiros2018 model is one of many models, published over 80 years that provide a fluid mechanical formulation for the filtered fraction (theory section). The functional form, as well as the asymptotic behavior of the filtered fraction predicted by alternative theories, varies substantially (Figure 16A).

In that respect, the Glauert1932 [48] model and the Rivera2011 [19] model represent two extreme behaviors, while the Steiros2018 model adopted here and its precursor, the Koo1973 model, are intermediate for the limiting behavior of φ as $s \rightarrow 0$. The prediction of the models for small solidity is especially important in the context of multi-layer collectors since their maximal ACE is attained for solid fractions below 0.3 (Figure 16B).

A comparative analysis of the design space for these models is also informative. Notably, although the models disagree on the maximum ACE that can be achieved for a given N , their respective ACE ridges follow similar arcs in design space (Figure 16B). Specifically, they all go through a small target area ($0.25 < s < 0.35$, $N = 4, 5$) where the multi-layer collectors achieve an efficiency

~ 40% better than the most efficient single-layer collectors. The quantitative agreement between the models shows the robustness of the efficiency optimization in the design space.

Interestingly, the subspace where η_{AC} is locally maximized follows closely curves of constant filtered fraction for all four models (Figure 17). Therefore, the improved aerodynamic collection efficiency of multilayer fog collectors comes almost exclusively from improvements in the incident fraction as new layers are added to the system.

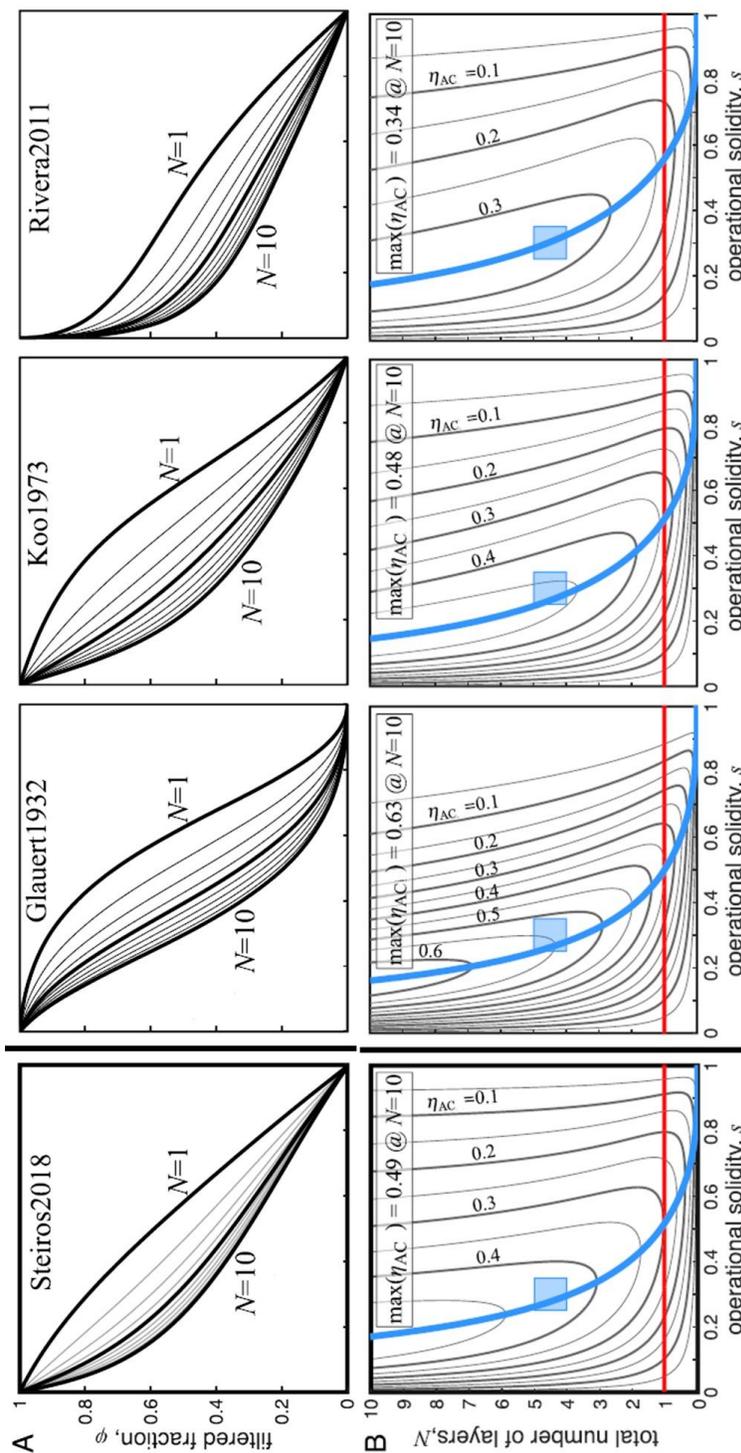


Figure 16: The ACE ridge of four alternative models for the filtered fraction. (A) The filtered fraction of the various models. Note the model-dependent form of the asymptotic behavior of $\varphi(s)$ as $s \rightarrow 0$. (B) Design space for the models listed in A. The blue subspace marks the region within which ACE is locally maximized, either at constant N (lower edge of the blue strip) or at constant s (upper edge of the blue strip). The red square is the suggested target design.

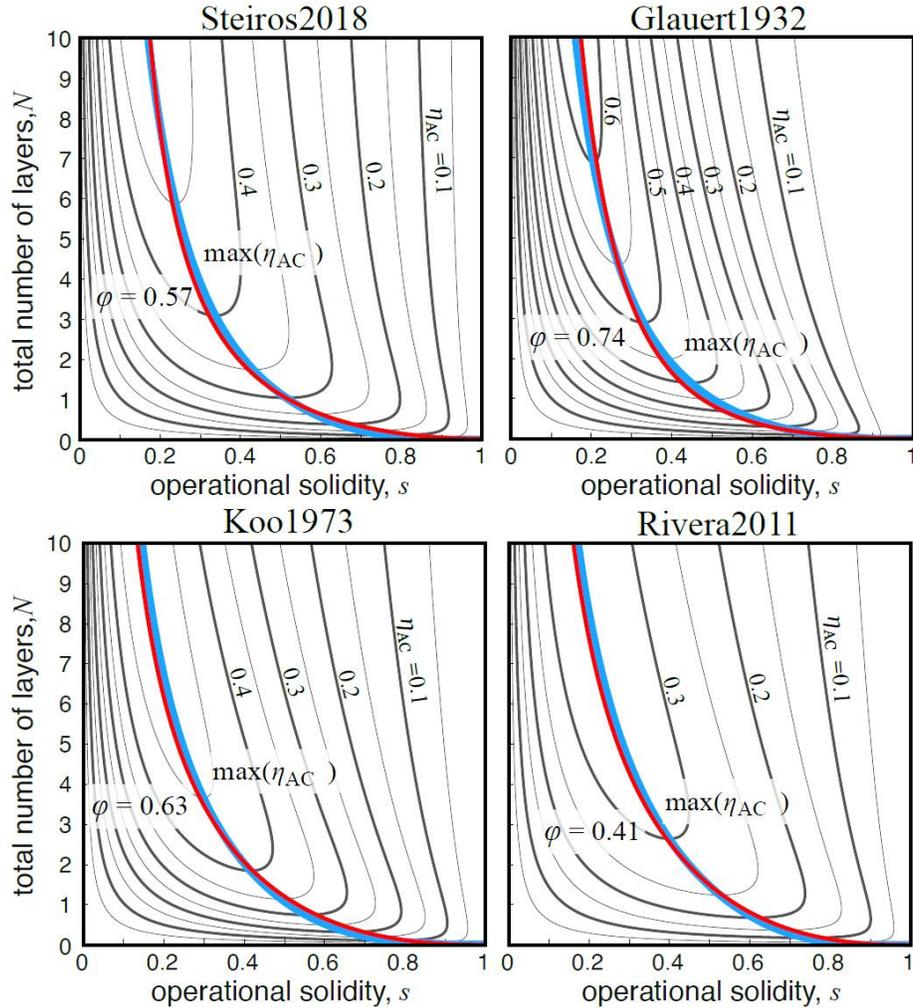


Figure 17: The $\max(\eta_{AC})$ subspace (blue curves) overlaps closely with level curves for the filtered fraction (red) in design space.

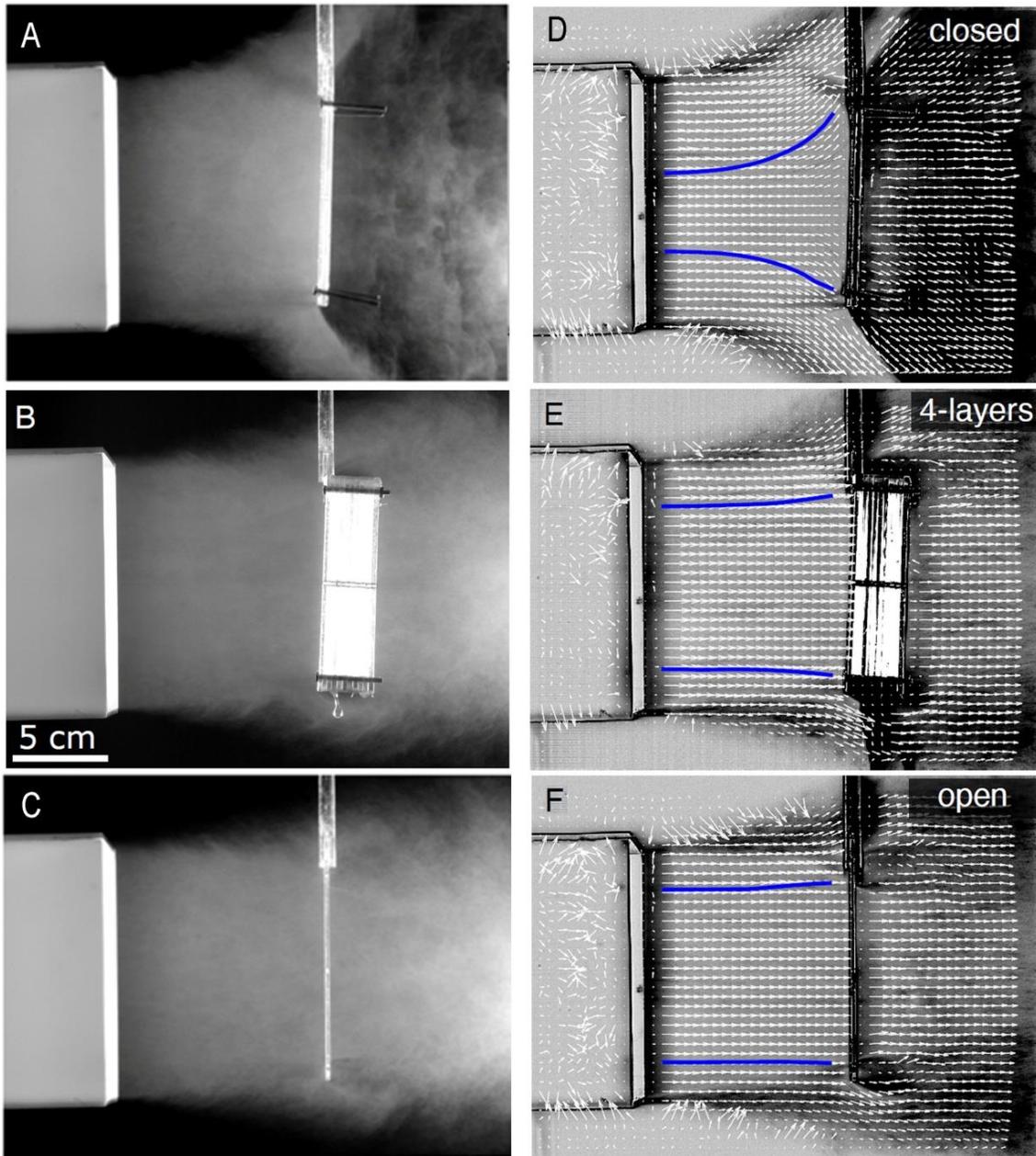


Figure 18: Measurement of ACE for a multi-layer harp collector ($s = 0.17$, $N = 4$). (A) Close-up of the fog jet filtering through a closed collector. (B) Close-up of the fog jet filtering through a 4-layer collector. (C) Close-up of the fog jet filtering through an open collector. (E) – (F) Recorded fog flow for a closed collector (E), a 4-layer harp (F), and an open frame (G). The blue curves indicate streamlines.

Because the models differ substantially in their predicted max ACE (from 34% to 63% for a 10-layer collector), we undertook a series of experimental observations to quantify the effective efficiency of multilayer collectors. As noted above, the equation for η_{AC} is first and foremost a statement about two geometrical ratios: the area ratio associated with the filtered fraction and the solidity s of the mesh (ratio of the obstructed area over the total area of one collector layer).

To assess the ACE, we developed a wind tunnel to produce realistic fog conditions in the laboratory (Figure 6). Experimenting with four-layer harp collector ($l = 100$ mm, $h = 2$ mm, $d = 0.150$ mm), we found an operating solidity of $s = 0.17$ (Figures 19A, B), giving an incident fraction of $\chi = 1 - (1-s)^4 = 0.53$. Integrating the flow field, we arrived at a filtered fraction of $\varphi_{obs} = (l_\infty / l)^2 = 0.81 \pm 0.016$ (Figures 20).

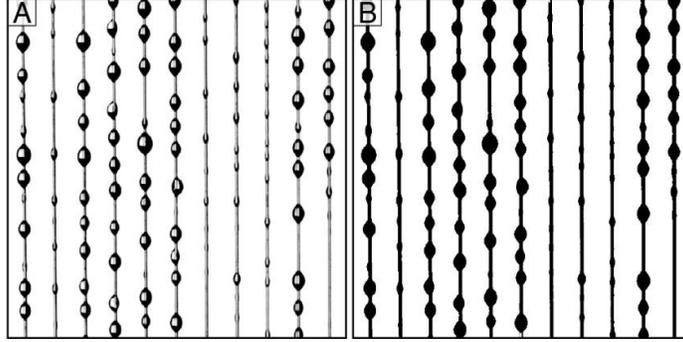


Figure 19: Operational shade coefficient of a simple harp (A) Photo of the mesh under operating conditions. (B) Binary (black/white) version of (A) Used to compute the solidity. The “dry” solidity is 0.075 while the “wet” solidity is 0.17.

Based on the measured incident and filtered fractions, the aerodynamics collection efficiency is $\eta_{AC} = \varphi\chi = 43\%$, which exceeds slightly the value of 37% predicted by the Steiros2018 model (Figure 14). The discrepancy arises in part because of the impossibility of measuring the flow field within 10 mm of the collector’s surface with our current experimental setup. The truncated velocity field leads to a slight overestimate of the filtered fraction (Table 3 and Figure 18D-F).

Given the care needed to measure ACE, it might be asked why it should be preferred as a performance standard over the total water collection efficiency, η_{tot} , as defined in Eq. 1. The reason is that although Eq. 1 appears tractable at first sight, a more detailed analysis (Eq. 6) reveals that η_{tot} involves the lost mass fraction, $\int_0^\infty \left(1 - \frac{d_\infty(r)}{d} s\right)^N m(r) dr$, where the terms $d_\infty(r)/d$ and $m(r)$ both depend on the radius of the droplets in the incoming fog. Notably, these two terms give, together, scaling on the order of r^5 (see the Theory section). Therefore, unless the probability density function for the droplet sizes, $f(r)$, is characterized precisely, the total water collection efficiencies are impossible to compare.

Table 3: The filtered fraction, φ , computed as a ratio of areas (l_∞^2 / l^2).

Collector	l_∞	l	l_∞^2 / l^2
four-layer harp	0.093	0.10	0.82
closed	0.047	0.10	0.21
open	0.096	0.10	0.88

In fact, it could be argued that due to its very nonlinear dependence on r , η_{tot} is virtually useless as a metric for efficiency because of its great sensitivity to the presence of rare but large droplets.

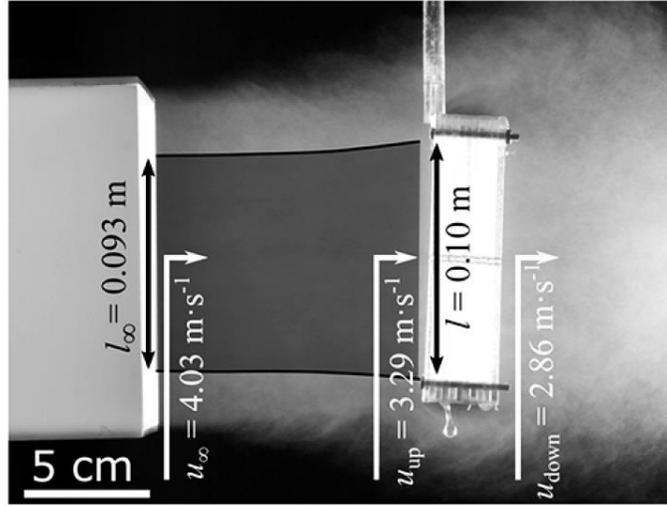


Figure 20: Close-up of the fog jet filtering through the collector with the key variables characterizing the flow field indicated.

In contrast, ACE is what is left of η_{tot} when factors affected by the droplet size distribution of fog are eliminated (Eq. 8). Moreover, ACE captures the fundamental trade-off for fog collection. Therefore, in an effort to increase the repeatability and portability of future research in fog collection, we propose the geometrical measurement of ACE as a potential standard for the field (Figure 21).

As a final validation of the performance of multilayer collectors, we compare their yield with that of the standard fog collecting medium—two plies of Raschel mesh (“dry” solidity $s = 0.6$) [49] without spacing between them and thus approximating a single-layer collector. As expected, the yield of the multilayer harps greatly exceeds that of the Raschel standard (Figure 12). Notably, even a single harp layer offers a slightly better yield than the two-ply Raschel mesh (Figure 22A).

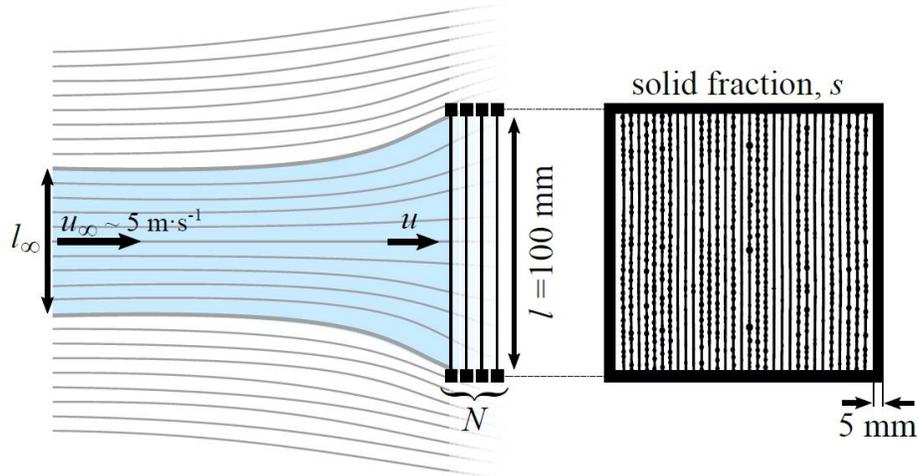


Figure 21: Proposed standard for the measurement of ACE. Prototypes should be square with 100 mm \times 100 mm of open area and a frame of 5 mm on all sides. The operational solid fraction s and the number of layers N are free parameters to be adjusted. The ACE should be measured at a free stream velocity close to 5 m \cdot s $^{-1}$ and in the presence of fog.

The poor performance of the Raschel mesh under well-defined laboratory conditions is explained by the fact that the two-ply mesh exceeds greatly the optimal operational solidity ($s_{Raschel} \approx 0.7$ vs $s_{opt} \approx 0.5$). While the multiharp designs outperform single-layer designs for all N , these collectors lose some of their yield for $N \geq 6$ (Figure 22A), a result that is not predicted from the design space. This efficiency loss probably arises because of the increasing boundary layer that develops in the vicinity of the collector frame.

In the case of a 10-layer collector, the frame depth exceeds 50 mm while the open area for filtration remains 100 mm \times 100 mm. In other words, for large N , the collector depth is such that the collector forms an increasingly long tube through which the fog stream must filter. Despite this limitation, the five-layer harp offered a four-fold increase in yield (Figure 22A).

These results were confirmed in field experiments with the 4-layer harp prototype shown in Figure 2A. During a period of low fog, the prototype collected 4.3 L \cdot day $^{-1}\cdot$ m $^{-2}$ while the two-ply Raschel mesh collected only 1 L \cdot day $^{-1}\cdot$ m $^{-2}$ (Figure 22B).

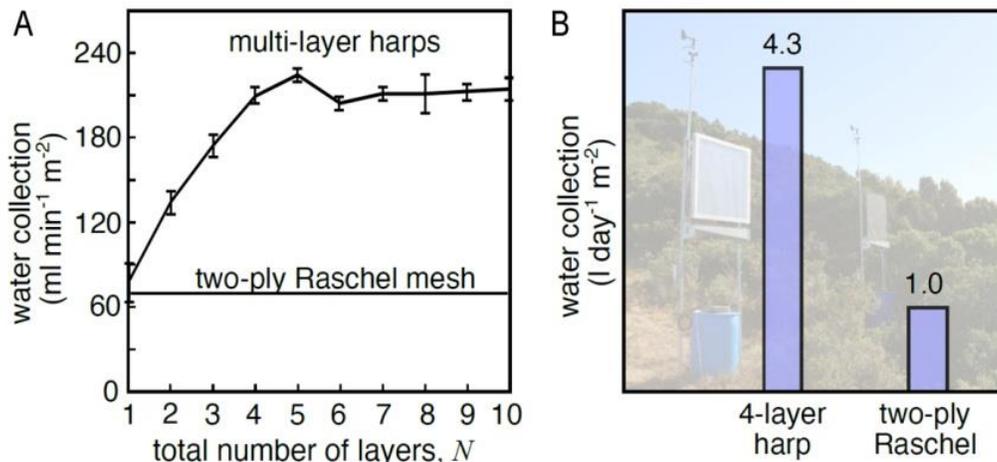


Figure 22: Yield measurements. (A) The yield of multi-layer harps ($1 \leq N \leq 10$, $s = 0.17$, inter-layer spacing of 6 mm) compared to two plies of Raschel mesh with $s = 0.7$ at a fog velocity $u_{\infty} = 4$ m \cdot sec $^{-1}$ (B) Field measurements of yield over 20 days.

5.2. Wettability of Vertical Harps for Fog Collection

Previously, Rajaram et al. 2016 [16] worked on the coating of Raschel meshes with Teflon, ZnO nanowires, and hydro beads to check the impact of coatings and surface hydrophobicity and found that the resulting modified mesh harvested 50% more water than of untreated Raschel mesh [16].

The movement of water droplets on a surface that is perpendicular to the gravity is quite faster advancing toward the tip along with the thin water boundary as reported in a previous study [50]. Hydrophilic mesh captured tiny droplets of fog efficiently with more affinity and transports to the tip of collector elements [51, 52].

In a contradiction, Ju et al. described that the hydrophobic surface provides a high growth rate to droplets and rolled them off [53]. Thus, the droplets clung to such surfaces do not spread easily [11]. Similarly, Garrod et al. reported that the hydrophobic surface of mesh harvested more fog than the hydrophilic [54]. Additionally, the surface should have enough adhesion force to collect the fog droplets along with the faster transport to the bottom of the mesh in its vertical orientation. The most favorable condition for an ideal collector element is to provide a free surface for the rebirth of fog droplets and drain them by gravitational force without clogging [23, 55].

For the hydrophobic surfaces, Wenzel and Cassie-Baxter's models showed how surface roughness can affect a water droplet's contact angle. In the Wenzel model, there are no air bubbles underneath the droplet and the droplet is in complete contact with the surface. The droplet sticks very well to the surface and it's called a pinned droplet. Therefore, the surface roughness quantifies by " r ", which is the real surface area divided by the projected surface area. Since every surface has some sort of roughness because no surface is completely smooth at the molecular level. It is assumed that $r > 1$. The Wenzel model states that $\cos \theta^*$ (apparent contact angle) is equal to r times $\cos \theta_E$ (equilibrium contact angle). In this state, water droplets will bounce or roll off. This is useful for water repellent and self-cleaning surfaces [56, 57].

Herein, we applied Silane coating on our prototype to make it hydrophobic. It provides low surface energy to the droplets on the surface of FCE and compels them to roll down rapidly. The component that imparts the capacity of an organosilane to create a hydrophobic surface is silane allocation on the surface, organic substitution, remaining unreacted groups of the silane and the amount of surface coverage. The organic substitution should be non-polar to create a hydrophobic surface.

The hydrophobic impact of the organic substitution may associate with the free energy of shifting hydrocarbon molecules from the aqueous state to the uniform hydrocarbon state. The plasma treatment incorporates hydroxyl group to enhance the water affinity while silane eliminates the hydroxyls as water adsorbing sites and supplies anchor positions for the non-polar organic substitution, which defends the polar entities from water interaction [58].

The hydrophilic-hydrophobic patterned surface by the inspiration of the Namibian beetle has been illustrated by many bioinspired designs. The design allows the moisture to be collect by hydrophilic bumps or trichomes on the hydrophobic surface with the strong driving force to drain water [59, 60].

6.2.1. Characterization

Static contact angle

Static contact angle evaluation of untreated and treated (hydrophilic and hydrophobic) samples was determined with a goniometer system (Kruss Easy Drop) using $0.5 \mu\text{l}$ (micro liter) of water drop and enlist the results as shown in Figure 23.

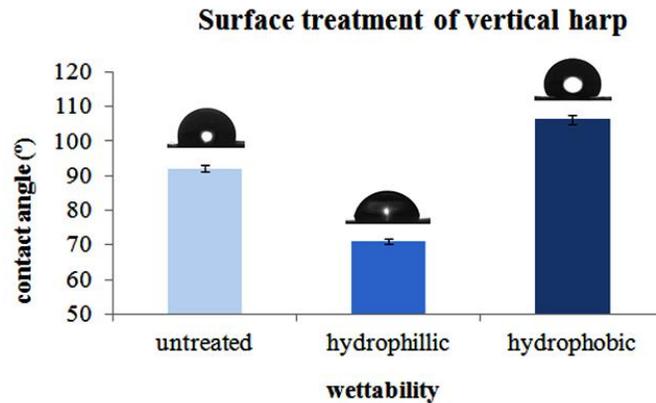


Figure 23: Contact angle results of untreated, hydrophilic surfaces and hydrophobic surfaces.

To calculate the yield, the untreated monofilament sample and treated samples with hydrophilic and hydrophobic surfaces were hung at a distance of 10 mm from the head of the fog generator for 30 minutes (Figure 8). The fog droplets were intercepted by the hanging samples and saved in a funnel guiding to a cylinder. The given results are shown in Figure 24. It is determined that the specimen with surface roughness and hydrophilic behavior presented a decline in fog collection in comparison with the untreated sample while the hydrophobic surface collected more water as shown in Figure 24. Indeed, distinct nature of the hydrophilic surface structure, the droplets coalesce on the hydrophilic spots and expand in volume, but do not leave until they attain a specific size, subject to the proportion and gravity, which decelerates the water collection dynamics. This behavior restricts the deposition of new incoming fog droplets on the monofilament [11]. On the other hand, the hydrophobic surface of the sample provides fast detachment from the surface due to weak solid-liquid interaction rather than the growth of water droplets. Eventually, the tiny droplets initiate to roll down on the tilted hydrophobic surface to the storage. Such structures have been utilized for the drag reduction in attribute to reduce the ability of contact angle between the surface and water droplet (surface wetted area) [61].

The droplet mobility on the hydrophobic surface depends on the WCA, direction of the droplet's movement, the surface morphology of the collector element, and physical characteristics of the droplet. A supplementary aspect that obscures this problem is the droplet pinning to some local sites which is hard to calculate precisely. It should take into account, absence of pinning effects, a theoretical method can be applied to determine contact angle hysteresis and the force of detachment from a single fiber [62].

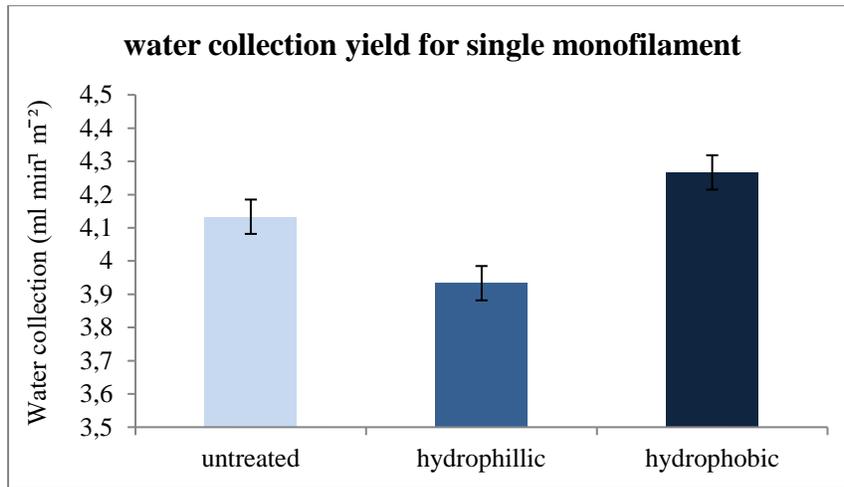


Figure 24: Water collection yield for single monofilament of all three samples.

It is specified that our hydrophobic monofilament sample does not demonstrate any substantial clogging as the hydrophilic monofilament sample does. The basic aim of surface modification was always to enhance the deposition of fog droplets and rapid transport to drainage.

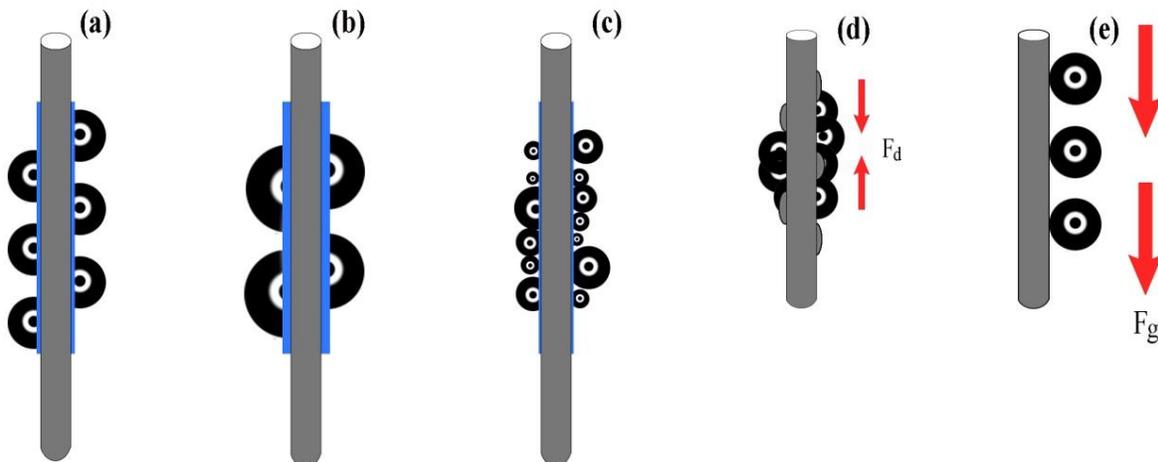


Figure 25: Display the position and shape of water droplets on the samples. (a) Illustration of fog on the untreated filament before slide down. (b) Demonstration of captured droplet areas of hydrophilic filament in the same length segment as an original filament with droplet area. (c) A bunch of small fog droplets adsorbs on the hydrophobic surface before it starts to roll down. (d) Driving force (F_d) produces a wettability slope of droplets on the surface of vertical FCEs dealt with plasma treatment. (e) The fog droplets grown on the hydrophobic surface approach the significant sliding volume and rapidly move along the vertical path with the force of gravity (F_g).

Generally, plasma treatment incorporates new oxygen-containing groups on polymer surfaces to contribute to the hydrophilicity [63] that leads to clinging the fog droplets for a long time. The coalesce of tiny droplets makes its size bigger on all sides of the tubular collector element (Figure 27a). Wetting also creates the water film around the surface which enhances the affinity of droplets

to collector samples. Meanwhile, the hydrophobic surface rolls down the droplets on which portion of the surface it is born as shown in Figure 27b.

AFM images of untreated and air-treated DBD plasma of PE monofilaments are shown in Figure 26. Dry air plasma-treated sample observed with small bumps on the surface extracting as surface roughness. This surface is supposed to catch oxygen-functionalities on the polymer chains and reduced the contact angle up to the saturated region [64].

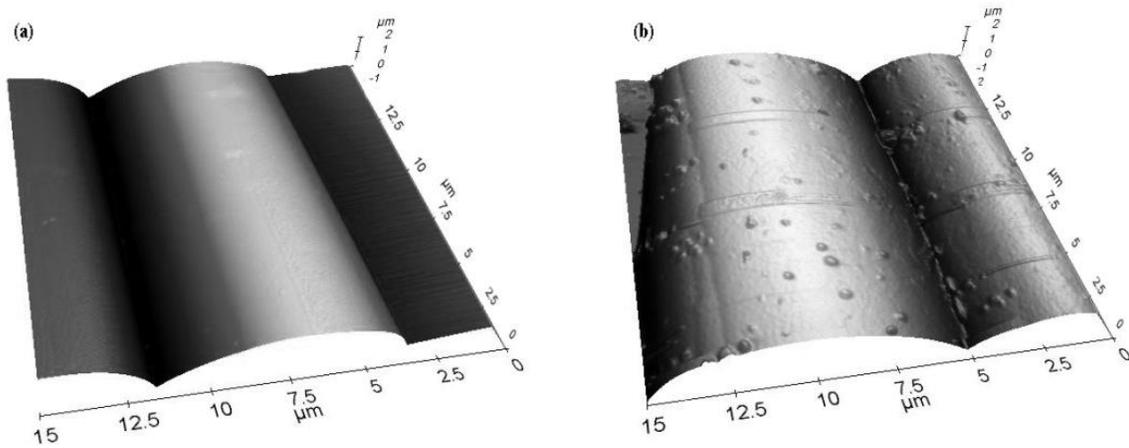


Figure 26: AFM images of (a) untreated and (b) dry air plasma treated PE monofilament samples.

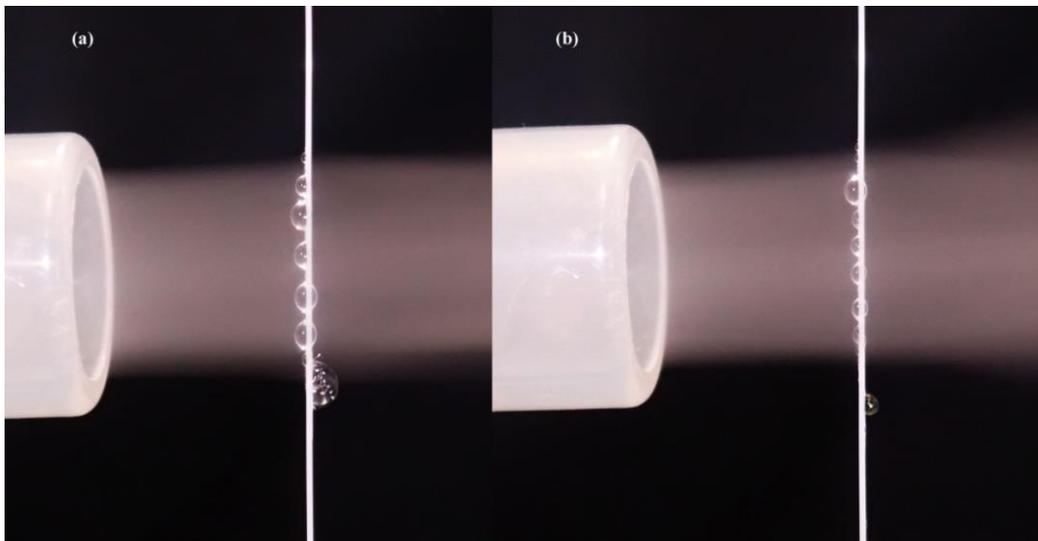


Figure 27: Deposition and adhesion of droplets to the monofilament. In (a), hydrophilic surface bond with droplet and provide enough time to make it bigger until it forces of gravity overcomes the weight of the droplet. In (b), the hydrophobic surface does not allow the droplets to be stayed there for a longer time and compel the droplets to roll down.

Contact angle hysteresis

The main purpose of adding the hydrophobic coatings to the FCE are to minimize the CAH of the droplets clung to the surface and hence transport to drainage. This effect also helps to understand why we keep the diameter of the collector element minimum. As described in previous studies [65, 66], the pinning force is caused by the formation of CAH. A droplet on a collector element may be in the barrel form or cling on the side of the collector element [67]. Herein, we observed both states for the falling droplets, but in the flow trajectory, it was clung on the side of the collector element as shown in Figure 27 (a,b). Moreover, the contraction in the size of droplets may be attributed to the reduction in pinning force that is linked with CAH as described in the following equation [68]:

$$f_p = -\sigma w(\cos\theta_r - \cos\theta_a) \quad (15)$$

Here f_p is the pinning force, σ is the surface tension and w is the width of the droplet while the minus symbol indicates the inverse direction of pinning force from the droplet flow. The reduction in CAH is attributed to the presence of hydrophobicity which may tend to the depinning of the surface contact and rapid shedding of droplets.

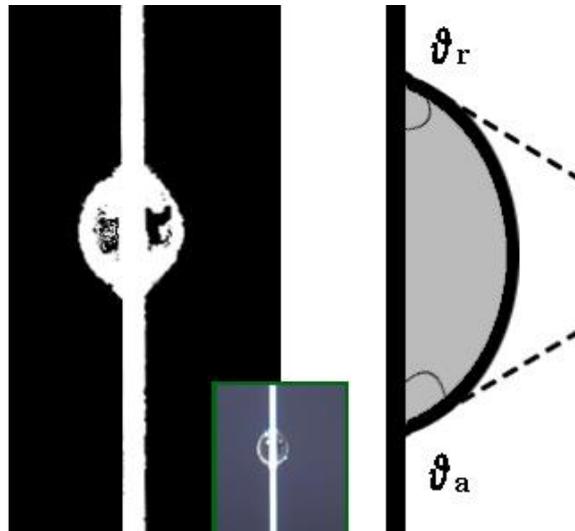


Figure 28: A water droplet on a vertical surface of fog collector element, caught at the critical advancing angle (θ_a) and the critical receding angle (θ_r).

It is quite hard to measure the CAH experimentally even on smooth surfaces. This calculation is generally in between the receding (θ_r) and advancing (θ_a) angles. The difference of both angles is empirically expressed as; $CAH = \theta_a - \theta_r$. As demonstrated in Figure 28, the CAH of untreated PE monofilament was about 6.2° while 7.6° and 5.1° was the measure for hydrophilic and hydrophobic surface respectively. It is seen that the CAH provided the most optimum stable level to encounter the gravitational force. It is also confined that the untreated surface exhibited the lowest hysteresis as compared to the hydrophilic surface. The contradictory, hydrophobic sample showed the lowest hysteresis in comparison with the untreated sample.

7. Conclusions and Future Work

In this research work, we have presented designs for optimally efficient passive fog collectors by focusing on a geometrical relation (Eq. 8) known as the aerodynamic collection efficiency (ACE). As we have shown, the maximal values of ACE are achieved only through the use of multilayer collectors whose efficiency can exceed 40% that of the best single-layer collectors. The analysis shows that taking into account the most effective use of materials, the optimal fog collector has $N = 4, 5$ layers and operating solidity $s = 0.3 \pm 0.05$, assuming that the operating thread diameter is sufficiently small to maximize inertial impaction of fog droplets. These conclusions were validated experimentally for multilayer harp collectors. When optimized, the latter can collect as much as four times that collected by the standard two-ply Raschel mesh, both under laboratory and field conditions.

Nowadays, researchers are specifically working on fog collection efficiency with surface modification methods to provide the droplets quick transportation and rolled them off to storage [53, 54, 60]. In our study, the FCE with hydrophobic treatment slightly improved the yield and efficiency of a multilayer fog collector. The major parameter is the structural design of the collector which enhances the productivity of the mechanism. The water collection yield of a single monofilament was enhanced by 107% by incorporating hydrophobic coating on the vertical collector elements. It is not possible to enhance the water collection yield by hydrophilic plasma treatment due to the clinging of fog droplets for a longer time and restrict the path of new coming droplets to be grown on the collector surface.

These findings show that surface hydrophobicity developed a slight modification on the surface and does prompt the process a little efficiently. In this fog harvesting study, we conclude that the water collection efficiency is mainly coupled with the design of the collection. This study could help to develop a large-scale fog harp that would be cost-effective and easy to install for fog harvesting. The manifestations of CAH enforced our results to include the hydrophobic coating for an efficient fog collection rate.

In the future, the mass production of multilayer harps would be much more efficient to collect the high yield of fog collection. Moreover; a parabolic fog collector could be more appropriate to catch a maximum fraction of fog particles.

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9. List of papers published by the author

9.1. Publications in journals

- [1] **Azeem M**, Guérin A, Dumais T, Camino L, Goldstein RE, Pesci AI, Rivera JD, Torres MJ, Wiener J, Campos JL, Dumais J. Optimal Design of Multilayer Fog Collectors. *ACS Applied Materials & Interfaces*. 2020, 12(6): 7736-7743
- [2] **Azeem M**, Wiener J, Noman MT, Petru M, Louda P. Structural Design of Efficient Fog Collector: A Review. *Environmental Technology and Innovation*. 2020, 101169.
- [3] **Azeem M**, Javed A, Khan MQ, Noman MT, Shahid M, and Wiener J. Hydrophillization of Polyester Textiles by Non-Thermal Plasma. *AUTEX Research Journal* 2021, 21(2): 142-149
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9.2. Contribution in conference proceeding

- [1] **Azeem M**, Wiener J, Khan MZ, , Havelka A, Shahid M. Hydrophobic Treatment of Nano-filament Polyester Fabric. 2017. *9th Central European Conference*, Liberec, Czech Republic.
- [2] **Azeem M**, Tomkova B, Hes L, Wiener J, Ali A. Thermal and Tactile Comfort of Nanofilament Fabric. 2018. *The 91st Textile Institute World Conference*. Leeds, UK.
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9.3. Citations

[1] **Azeem M**, Guérin A, Dumais T, Camino L, Goldstein RE, Pesci AI, Rivera JD, Torres MJ, Wiener J, Campos JL, Dumais J. Optimal Design of Multilayer Fog Collectors. *ACS Applied Materials & Interfaces*. 2020, 12(6): 7736-7743

- Cited in 12 articles

[2] **Azeem M**, Wiener J, Noman MT, Petru M, Louda P. Structural Design of Efficient Fog Collector: A Review. *Environmental Technology and Innovation*. 2020, 101169.

- Cited in 10 articles

[3] **Azeem M**, Boughattas A, Wiener J, Havelka A. Liquid Water Transport mechanism in fabric; A Review. *Vlakna a textil*. 2017, 24(4): 58-67

- Cited in 16 articles

Curriculum vitae

Personal information	
First name / Surname	Musaddaq Azeem
Address	17 Listopadu 584, 460 15 Liberec, Liberec XV Stary Harcov. Czechia.
Mobile	+420 775 314 882
E-mail(s)	musaddaqazeem@yahoo.com musaddaq.azeem@tul.cz
Nationality	Pakistani
Place and Date of birth	Toba Tek Singh (Pakistan) on 2 th Nov 1986
Status and Gender	Married; Male
Work Experience	
Dates	06/2013 to 01/2014
Occupation or position held	Asst. Weaving Manager (Warping, Sizing, Weaving, Quality Control) SHAHRAJ Fabrics (Pvt.) Ltd, Lahore, Pakistan
Dates	2/2010 to 10/2010
Position	Officer (Commercial production & planning control), Masood Textile Mills Limited, Faisalabad, Pakistan
Education and Training	
	12/2015 - till now
Title/ Qualification	Ph.D. (Textile Engineering)
Thesis topic	<i>Scientific Design of Multilayer Fog Collectors</i>
University	Technical University of Liberec, Faculty of Textile Engineering, Department of Material Engineering
	01/2011 - 03/2013
Title/ Qualification	MS Textiles (Master)
Thesis topic	<i>Technical factors affecting the quality on the projectile weaving with Open End and Ring spun yarn</i>
University	University of Management and Technology (UMT), Lahore, PAKISTAN
	09/2006 - 03/2010
Title /Qualification	MSc (MASTER'S Fiber Technology)

Thesis topic	<i>Technological studies on dyeing behavior of acrylic fabric and its blend with polyester</i>
University	University of Agriculture, Faisalabad (UAF), Faculty of Agriculture Engineering, Department of Fiber & Textile Technology.
Internships	National Textile University, Pakistan (2016) Shinshu University, Ueda City, Japan (2017) Ghent University, Belgium (2018) Drexel University, Philadelphia, USA (2018) Adolfo Ibáñez University - Campus Viña del Mar (2018, and 2019)
Phd Supervisor	prof. Ing. Jakub Wiener , Ph.D.

Brief description of the current expertise, research and scientific activities

Brief description of the current professional research and scientific activities including mainly information on doctoral studies, teaching activities, research and other projects the student took part in.

Doctoral studies	
Studies	Textile Engineering Textile Technics and Materials Engineering full time
Exams	Structure and Properties of Textile Fibers, KMI / D07, 18.04.2016 Differential Equation, KAP / D41, 13.06.2016 Heat and Mass Transfer in Porous Media, KHT / D17, 23.01.2017 Sorption Processes, KMI / D13, 27.02.2017 Experimental Technique of Textile, DFT / D33, 08.11.2019
SDE	State Doctoral Exam completed on 04.12.2020 with the overall result passed.
Teaching Activities	
Teaching	Course title 1, time of instruction
Leading Bachelors/ Master students	Name of student, title of thesis, year defence
Research projects	1) Student Grant Scheme (SGS 21200) by Technical University of Liberec, Czech Republic, (project participant), 2017. 2) Student Grant Scheme (SGS 21313) by Technical University of Liberec, Czech Republic, (project participant), 2019.
Other projects	

Recommendation of Supervisor

Supervisor's opinion on Ph.D. thesis of Mr. Musaddaq Azeem, M.Sc.

I have known Mr. Musaddaq Azeem since 2016.

His Ph.D. thesis is entitled "Scientific Design of Multilayer Fog Collectors" in the field of study "Textile Technics and Materials Engineering".

This dissertation is focused on the optimal design of multilayer fog collectors and the surface wettability of vertical harps of fog collectors. This research work highlighted the appropriate structures and designs beneficial for increasing the water collection efficiency and fog harvesting phenomenon. Fog harvesting techniques would have to consider a particular scope to advance the habitable and sustainability of this earth.

During his Ph.D., he validated his skill to execute high-quality research, with motivation and hard work. Naturally, he needed guidance, but once the goal was set, he performed very well to reach goal. It is very pleasant for me to see him working on a high level of research that is valuable for mankind and living organisms on the earth.

He has published 16 articles in highly impact factor journal, of which he is the first author in 10 articles. All published articles reflect the orientation related to his Ph.D. work. He completed most of his experimental work at Chile in Adolfo Ibáñez University - Campus Viña del Mar, where his local co-supervisor was Prof. Dr. Jacques Dumais.

Consequently, I recommend Mr. Musaddaq Azeem's thesis be accepted for defense.

prof. Ing. Jakub Wiener, PhD.
Supervisor

Reviews of the opponents



Posudek doktorské práce

Uchazeč: Musaddaq Azeem, M.Sc.

Název práce: Scientific Design of Multilayers Fog Collectors

Pracoviště: Textilní fakulta, Technická Univerzita v Liberci

Oponent: Petr Henyš, TUL, NTI

Evaluation of the significance of the dissertation for the field

The thesis is devoted to a theoretical analysis of the influence of the structural properties of the fog collector on its efficiency and resulted in a modification that significantly increased the efficiency of current multilayer collectors. Furthermore, the reviewer appreciates the proposal of standardization of laboratory measurements, which is crucial for a repeatable comparison of newly designed and original collector types. Considering the topicality of the issue, the opponent considers the results of the work very satisfactory with the possibility of practical application in areas with low availability of domestic water.

Evaluation of the problem-solving process, the methods used and the achievement of the stated goal

In the first part of the thesis, the author summarizes the current state of knowledge and introduces the theoretical models that allow to determine the efficiency of the water harvesting process. In the design of the collector, the author adopts a combinatorial approach, sometimes without obvious explanation: for example, why did the author consider four different materials for the construction of the collector? The author has apparently built several collectors, but according to the opponent, he has not shown them sufficiently in the experimental part: for example, Figure 8 is a cut-out for which it is not clear where it is from and what the red circles mean. The same is true of the experimental setup in Figure 10. It is not clear whether the author designed and built this device himself or not. The choice of the appropriate material for the collector is slightly messy, as it is not clear what 'exact' properties the author has in mind and what literature he is referring to.

Opinion of the opponent on the original results of the author of the dissertation

The author has carried out an exhaustive number of experiments, including the preparation of his own laboratory equipment. However, the most important contribution of the author is the systematic design of a multilayer collector with increased wettability of the base material. Furthermore, the referee appreciates the author's confrontation of experimental results with theoretical models and their optimization.

Systematicity and formality of work and publications

From the formal point of view, the work does not deviate from the standard. In some places there is "ambiguous" information in the work, for example, see the note on the selection of a suitable material for the collector. Considering the number of experiments performed, the referee considers



that the thesis could contain more details and, for example, a suitable chart showing the structure and order of the experiments and their interconnection.

The author's original work has resulted in several publications in high quality journals, in particular the article in ACS Applied Materials & Interfaces is considered by the opponent to be very useful and clearly demonstrates the author's ability to conduct independent scientific research and to present results in a coherent form. Despite criticisms of some of the author's practices, which do not in any serious way call the author's work into question, the referee is convinced that Azeem Musaddaq is worthy of the degree of PhD.

V Liberci

Petr Henyš



Opponent Evaluation of Dissertation Thesis

Name of Thesis: Scientific Design of Multilayer Fog Collectors

Author: Musaddaq Azeem, M.Sc.

Evaluated by: Doc.Ing. Josef Dembický, PhD.

The submitted dissertation work is concerned with the proposal of fog collectors. It is focused on the multilayer collectors with optimized porosity of the collecting net. In the experimental part there are tested harp collectors. The aim of the thesis is to find an optimal design of collectors and on top an optimal surface properties of the collector element. There is compared the impact of hydrophilicity performed by plasma treatment and hydrophobicity performed by silicone treatment on the final efficiency of the collector. Based on experimental results the author proposes as optimal a collector with 4-5 layers and further the application of hydrophobic treatment on the polyethylen matrix based on silicone.

The thesis is written in english, it has got 78 pages with 7 main chapters and 28 subchapters. In the theoretical part there is included literature review and theory. The description is very detailed and well structured. In the experimental part there is described the research methodology, further the results and conclusion. The Author drew from 132 sources, he published 18 articles in the research journals in the time period 2017-2021, whereas 5 articles were focused on the topic of this dissertation. Further, he published 4 contributions in the international conferences in the time period 2017-2019. The author was 38x cited in research journals.

I have got these formal remarks to the thesis:

1. In the table of contents page ii chap. 3.3.2 is written in incorrect format
2. In the table of contents page iii the chap. „Wettability of Vertical Harps for Fog Collection“ is incorrect described as 5.2 (correct shall be 6.2)
3. Page 10 – incorrect described equation $LFC = \dots$
4. In the thesis the descriptions of parameters and units are sometimes confused described
5. Page 28 the last sentence there is incorrect mentioned the word „experimental“

6. Page 47 – incorrect mentioned the symbol in the description – Fig. (E) instead of Fig. (D)

I have got following questions to the author:

1. In chapter 6.1 there was determined that the optimal layer distance for the maximal water yield is 6 mm. How this fact can be explained?
2. Explain the term surface energy of materials. What values of surface energy do correspond to the tested material polyethylen and how do these values differ from the energies of materials which were in the study also considered to be used?

In the end I state that the dissertation thesis fulfills the specified criteria and I recommend it to the defense.

In Frýdlant, 12.1.2022

Doč. Ing. Josef Dembický, PhD.