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Enhancement of fog-collection efficiency of a Raschel mesh using surface coatings and local geometric changes

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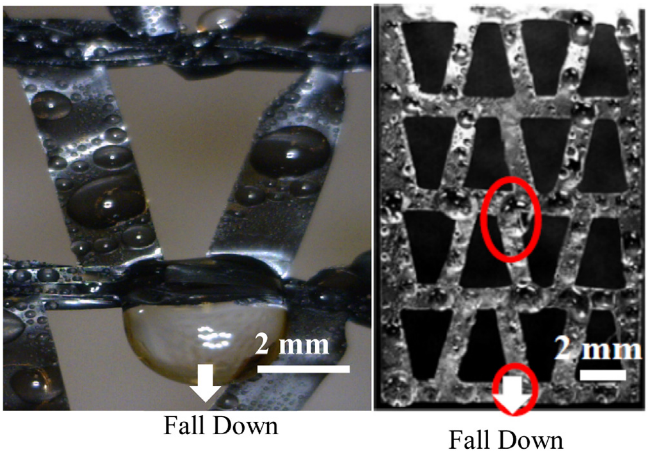
HIGHLIGHTS

- In this work, we explored the possibility of enhancing fog-collection efficiency of typical Raschel meshes, which have been widely used to collect fog in a few countries, such as Chile.
- We found that a superhydrophobic coating resulted in about 50% enhancement in the collection efficiency, and developed a simple model to explain the reason behind this enhancement.
- We also observed that the reduction of pore size, together with the increase of the distance between two inclined filaments, yielded another 50% enhancement, and found that different pathways of drops resulted in this enhancement.
- After the surface modification and local geometric changes, the resulting mesh has collected water about 2 times that of a typical Raschel mesh.
- In addition, we also developed a new punching process to fabricate mesh-like structures out of polymer sheets.

GRAPHICAL ABSTRACT



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ABSTRACT

In a few countries, such as Chile, Raschel meshes are widely used in the field to collect fog. In this work, we explored the possibility of enhancing fog-collection efficiency of typical Raschel meshes. We found that a superhydrophobic coating resulted in about 50% enhancement in the collection efficiency, and that the reduction of pore size, together with the increase of the distance between two inclined filaments, yielded another 50% enhancement. After the surface modification and local geometric changes, the resulting mesh has collected water about 2 times that of a typical Raschel mesh.

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1. Introduction

In addition to energy, the issue of water shortage and scarcity is one of major global concerns, since about one billion people living in rural areas of African, Asian, and Latin American countries do not have access to clean water sources [1]. A water shortage has been a major problem faced by the modern civilization in both arid and humid environment [2]. In an arid environment with little rainfall every year, fog may be an important water source to some desert plants and animals, such as the cactus *Opuntia microdasys* [3], which originates from Chihuahua Desert, the Namib dune bushman grass *Stipagrostris sabulicola* [4], the species *Tillandsia landbecki* in coastal Atacama [5], mesophytic geophytes in Namaqualand and the Little Karoo [6], and the Namib tenebrionid beetle *Stenocara* [7,8]. A few artificial fog collectors have been recently developed [7,9–24]. Most of them mimic the fog-collection mechanisms of the aforementioned cactus [9–16] and beetle [7,17–21]. On the other hand, these collectors appear still at the stage of laboratory research, and have not yet been applied in the field.

For the last two decades, in at least five countries, such as Chile, the most commonly used large fog collector in the field employs a Raschel mesh that is vertically oriented between two poles to collect water from fog [25–28]. The Raschel mesh has meter-scaled lengths and widths, and it also has mm-scaled pores and filaments (Fig. 1(a)). The pores of a Raschel mesh have approximately triangular shapes, and some filaments are inclined with lengths close to 1 cm (Fig. 1(b)). The filaments are about 20 μm thick, while their joints are 200–400 μm thick. Fog is composed of tiny water drops with diameters in the range of 1–40 μm. The fog collection includes two steps. Tiny drops that are carried in a wind hit and accumulate on filaments. Under gravity, large drops, which are formed due to the coalescence of the tiny drops, may drain off from the filaments to an underneath gutter. Raschel meshes are effective in fog collection. Their fog collection rates are typically 1–10 L/m^2 per day [28]. Also, the presence of light rain with the fog has produced collection rates as high as 300 L/m^2 per day for a wind speed of 10 m/s [28]. On the other hand, there is a large room to improve their fog-collection efficiency. According to recent experimental results, only around 2% of water drops that pass by a typical Raschel mesh have been collected by this mesh [24]. In contrast, an optimal mesh with rectangular pores has shown a five-time enhancement in the fog-collection efficiency of a typical Raschel mesh [24]. Meanwhile, it has already been demonstrated that Raschel meshes are effective to harvest water in the field. Therefore, a Raschel mesh should have its unique advantages in collecting fog.

Using woven polyolefin Raschel meshes (Fig. 1), Schemenauer, Cereceda, and their co-workers have conducted numerous pilot-scale studies that demonstrate the feasibility of collecting fog [28–32]. However, as commented in ref. 24, most studies on mesh-based fog harvesters have been performed in the field using uncontrolled natural fog conditions, and systematic studies of these fog harvesters under laboratory conditions have been rare [27–32]. Under controlled laboratory conditions, Azad et al. have recently explored the effect of wettability on the fog collection of a double layered polyolefin Raschel mesh [12]. They found that the amount of water collected by superhydrophilic mesh was about 5 time that of a hydrophilic (untreated) mesh, and that a hydrophobic mesh collected 2.5 times higher amount of water than the hydrophilic one. Their results indicate that the enhancement of either surface hydrophilicity or hydrophobicity may increase fog-collection efficiency. The superhydrophilic mesh has been previously shown to be effective in fog collection [12]. In this work, we consider the effect of surface hydrophobicity, with particular attention to that of superhydrophobic coating. We also explore the influence of the changes in filament dimensions and orientations. Although double layered Raschel meshes are usually used in the field, our investigation is focused on a single layered one. A good understanding of its fog-collection behavior may lead to a better application of the double layered ones.

2. Theoretical background, and comparison tests

2.1. Theoretical background

The collection efficiency, η, of a mesh depends on aerodynamic collection efficiency (η_{ace}), capture efficiency (η_{cap}), and draining efficiency (η_{dra}) [27]:

$$\eta = \eta_{ace}\eta_{cap}\eta_{dra}. \tag{1}$$

All of these three efficiencies are not larger than 100%. η_{ace} is the fraction of the unperturbed water flux heading towards a mesh that would collide with the mesh filaments. η_{cap} is the fraction of the collided water drops that actually deposit on filaments from the fog flow initially headed toward the filaments. η_{dra} is the fraction of the deposited water that would drain off from the filament, which is subsequently collected through a gutter located at the bottom of the mesh.

η_{ace} is related to shade coefficient (SC), which is the ratio of the filament area over the total mesh area. η_{ace} does not necessarily increase with the decrease in the pore area. The expression of η_{ace} is [27]

$$\eta_{ace} = \frac{s}{1+\sqrt{\frac{C_o}{C_d}}}, \tag{2}$$

where s represents SC, C_d is the drag coefficient for the overall structure and approximately equals 1.18 for a Raschel mesh, and C_o is the pressure loss coefficient. C_o is related to s by [27]

$$C_o = 1.62[1.3s + \frac{s^2}{(1-s)^2}]. \tag{3}$$

According to Eqs. (2) and (3), η_{ace} is only 9% for a solid plate, which has no pores. It is 20% for a typical Raschel mesh, whose SC ranges from 35 to 37%. However, η_{ace} can be easily improved to the maximum value of 24.5% if SC is 55%, when the filament area of a typical Raschel mesh is increased relative to the pore area.

Langmuir and Blodgett have previously derived an empirical expression of η_{cap} for a circular cylinder [33]. This expression, together with Eq. (2), was adopted in ref. 24 to optimally design rectangular meshes, which have circular filaments. Since the filaments of a Raschel mesh have rectangular cross-sections, instead of circular ones, the empirical expression of η_{cap} may not be applicable to the Raschel mesh. In addition, we have not seen any theoretical models for η_{dra}. Thus, we would like to have a good understanding about these two efficiencies through experiments.

2.2. Comparison tests

Fog-collection experiments were performed on different meshes using an experimental setup shown in Fig. 2. Each test is conducted at room temperature (24 °C ± 1 °C). Two humidifiers (model: EE- 5301, Crane USA Co., and AOS 7135 Ultrasonic, BONECO USA Co.) are connected together to generate enough mist to cover a tested sample. A plastic pipe is employed to guide this mist flow. A fan (model: Breeze color USB Desktop fan, Arctic USA Co.) is used at 800 rounds per minute to increase the mist flow speed. At the end of the pipe, the mist flow speed is 1.1 m/s, which is measured using a wind speed meter (model: WM-2 Handheld Weather meter, AmbientWeather USA Co.). The entire process is conducted in a closed chamber with dimensions of 74 × 31 × 30 cm^3 (length × width × height). 100% humidity is maintained inside the chamber, and a humidity meter (model: Hydro-