

# **Droplet Capture and Water Transport on Thin Fibers for Water Harvesting**

by

Yunqiao Huang

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## **Examining Committee Membership**

The following serves on the Examining Committee for this thesis. The decision of the Examining Committee is by majority vote.

External Examiner:

Dr. Ali Dolatabadi

Professor, University of Toronto

Supervisors:

Dr. Zhongchao Tan

Adjunct Professor, University of Waterloo

Professor, Eastern Institute of Technology

Dr. Xianguo Li

Professor, University of Waterloo

Internal Member:

Dr. Zhao Pan

Assistant Professor, University of Waterloo

Internal Member:

Dr. Andrew Milne

Associate Professor, University of Waterloo

Internal-external Member:

Dr. Eric Croiset

Professor, University of Waterloo

## **Author's Declaration**

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

## Abstract

Water harvesting is a potential solution to the challenge of water scarcity. Among all harvesting techniques, fog harvesting is a promising option, which uses permeable collectors to capture droplets from fog streams. The structure of the collector is the key to achieving high water collection efficiency. The fast-growing demand for efficient collectors requires research into the structural design of fog collectors.

Fiber-based collectors have received considerable attention among all the structures of fog collectors. Generally, fibers can be woven into flexible grids or meshes, which are naturally permeable to serve as fog collectors. In addition, thin fibers that benefit droplet capture can be easily fabricated via multiple mature spinning techniques. Furthermore, functional structures can be created on fibers, enhancing water transport for efficient fog harvesting. However, gaps exist in the design of fiber-based collectors in terms of the effects of grid structure and waterdrop clogging on water collection efficiency. In addition, existing fiber-based collectors with water-transport ability rely on the creation of complex fiber morphologies, which hinders the large-scale application due to difficult fabrication.

This thesis study aims to fill the gaps in fiber-based collector design by obtaining knowledge in terms of droplet capture and water transport on thin fibers. The thesis starts with developing a multi-scale numerical model for fog harvesting to understand the effect of fiber grid structure on water collection efficiency. The numerical model can simulate fog harvesting at two extreme length scales that are comparable to collector scale at the large end and fiber scale at the small end. The results confirm two important effects of fiber grid geometries on water collection efficiency. First, dense thin-fiber grids negatively influence the collection efficiency because of the wall effect caused by viscous boundary layers. Second, the sparse thin-fiber grids can benefit from isolated clogging waterdrops and maintain relatively high efficiency when clogging blocks multiple grid openings. The two identified effects are then included to develop a new performance map for fog collectors, thereby shaping new design rubrics for fog harvesting.

Then, the experimental study of droplet capture on microfiber grids is carried out to understand the positive clogging effect. Microfiber grids are fabricated by NFES with the structural design guided by the obtained performance map. The results show that waterdrops clog the grid openings with a pattern that small waterdrops satellite large ones. Due to the small

fiber diameter, the waterdrops are "visible" to incoming airflow and strongly affect droplet capture. The large waterdrops deflect incoming fog flow towards the small ones, and the small waterdrops efficiently capture the fog droplets. Consequently, the fog collectors based on microfiber grids demonstrated an exceptional water collection efficiency of up to 21.4%. The micro-fiber grids require minimal material usage and no special surface treatment, highlighting a potential in fog harvesting.

Last, this thesis study discovers the water transport on ribbon-like fibers due to the long-wave Plateau-Rayleigh instability. The experimental study reveals that the deposited fog water is aggregated on the broad side of the fiber, where the low surface curvature triggers Plateau-Rayleigh instability with long wavelengths. The resulting drops are connected by a flowing film, which continuously transports water over centimeter-scale distances without the presence of external driving forces. A particle-image velocimetry analysis reveals that a pair of opposing flow exists in the film and forms organized vortices within the shear layer, which are explained by capillary effects on film-wise flow. Based on the long-wave Plateau-Rayleigh instability, a rivulets-on-fiber structure is developed using liquid bridges as artificial drops to continuously transport liquid over a 10 cm<sup>2</sup> fiber grid. The unique characteristics of water transport on the ribbon-like fibers and fiber grids provide new prospects for efficient collector design with simple fabrication methods.

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## List of Symbols

| Notation           | Term                                           | Unit                       |
|--------------------|------------------------------------------------|----------------------------|
| $A$                | Kuwabara coefficient                           |                            |
| $A_b$              | Area of obstacle                               | $\text{m}^2$               |
| $A_c$              | Area of collector                              | $\text{m}^2$               |
| $A_w$              | Projected area of waterdrops                   | $\text{m}^2$               |
| $a$                | Fiber (major) radius                           | $\text{m}$                 |
| $b$                | Fiber minor radius                             | $\text{m}$                 |
| $Bo$               | Bond number                                    |                            |
| $Bo$               | Critical Bond number for drop shedding         |                            |
| $C_c$              | Buckingham correction factor                   |                            |
| $C_p$              | Pressure loss coefficient of collector         |                            |
| $C_0$              | Drag coefficient of impermeable plate          |                            |
| $C_1$              | Viscous loss coefficient                       |                            |
| $C_2$              | Inertial loss coefficient                      |                            |
| $C_D$              | Drag coefficient of fiber grids                |                            |
| $c$                | Relative size difference of waterdrops         |                            |
| $D_p$              | Particle diffusion coefficient                 | $\text{m}^2 \text{s}^{-1}$ |
| $d_b$              | Obstacle diameter                              | $\text{m}$                 |
| $d_{\text{fiber}}$ | Fiber diameter                                 | $\text{m}$                 |
| $d_{\text{fog}}$   | Droplet diameter                               | $\text{m}$                 |
| $d_{\text{th}}$    | Threshold obstacle size                        | $\text{m}$                 |
| $E$                | Water collection efficiency                    |                            |
| $e$                | Euler's number                                 |                            |
| $F$                | Force                                          | $\text{N}$                 |
| $f$                | Fractions of wetted/unwetted areas             |                            |
| $g$                | Gravitational constant                         | $\text{m s}^{-2}$          |
| $H$                | Dimensionless film thickness for forward flow  |                            |
| $H_b$              | Dimensionless film thickness for backward flow |                            |

|           |                                                       |                    |
|-----------|-------------------------------------------------------|--------------------|
| $H_t$     | Dimensionless film thickness for film-drop transition |                    |
| $h$       | Water film thickness                                  | m                  |
| $h_c$     | Critical film thickness                               | m                  |
| $J$       | Dimensionless water flux                              |                    |
| $j$       | Volumetric water flux                                 | $\text{m s}^{-1}$  |
| $Kn$      | Knudsen number                                        |                    |
| $k$       | Boltzmann constant                                    | $\text{J K}^{-1}$  |
| $L_d$     | Diameter of collector domain                          | m                  |
| $L_t$     | Thickness of collector domain                         | m                  |
| $L_{sl}$  | Dimensionless thickness of shear layer                |                    |
| $l_{cp}$  | Capillary length                                      | m                  |
| $l_{sp}$  | Fiber spacing of fiber grids                          | m                  |
| $l_{1-4}$ | Fiber spacing for ROW structure                       | m                  |
| $l_w$     | Waterdrop spacing                                     | m                  |
| $Pe$      | Peclet number                                         |                    |
| $p$       | pressure                                              | Pa                 |
| $Q$       | Mass flow of fog water                                | $\text{kg s}^{-1}$ |
| $Q_c$     | Mass flow of collected fog water                      | $\text{kg s}^{-1}$ |
| $q_0$     | Dimensionless wave number of perturbation             |                    |
| $q$       | Dominating dimensionless wave number                  |                    |
| $q_c$     | Critical dimensionless wave number                    |                    |
| $Re_f$    | Fiber Reynolds number                                 |                    |
| $Re_d$    | Droplet Reynolds number                               |                    |
| $R$       | Dimensionless drop radius                             |                    |
| $r$       | Drop radius                                           | m                  |
| $r_c$     | Clogging drop radius                                  | m                  |
| $r_{th}$  | Threshold drop radius                                 | m                  |
| $r_w$     | Wetting radius of drop                                | m                  |
| $SC$      | Shade coefficient                                     |                    |
| $SC_w$    | Shade coefficient of clogging waterdrops              |                    |

|                      |                                                               |             |
|----------------------|---------------------------------------------------------------|-------------|
| $Stk$                | Fiber Stokes number                                           |             |
| $Stk_c$              | Clogging drop Stokes number                                   |             |
| $T$                  | Temperature                                                   | K           |
| $t$                  | Time                                                          | s           |
| $u$                  | Fluid velocity                                                | $m\ s^{-1}$ |
| $U$                  | Dimensionless velocity                                        |             |
| $U_f$                | Dimensionless forward velocity                                |             |
| $U_b$                | Dimensionless backward velocity                               |             |
| $u_0$                | Airflow velocity                                              | $m\ s^{-1}$ |
| $u_p$                | Airflow velocity penetrating collector                        | $m\ s^{-1}$ |
| $u_f$                | Forward flow velocity                                         | $m\ s^{-1}$ |
| $u_b$                | Backward flow velocity                                        | $m\ s^{-1}$ |
| $u_s$                | Mean airflow velocity approaching small waterdrop             | $m\ s^{-1}$ |
| $u_l$                | Mean airflow velocity approaching large waterdrop             | $m\ s^{-1}$ |
| $u_{th}$             | Capillary flow velocity that thins shoulder film              | $m\ s^{-1}$ |
| $v$                  | Droplet velocity                                              | $m\ s^{-1}$ |
| $y_b$                | Boundary layer thickness                                      | m           |
| <b>Greek letters</b> |                                                               |             |
| $\gamma$             | Surface tension of liquid-vapor interface                     | $N\ m^{-1}$ |
| $\gamma_{ls}$        | Surface tension of liquid-solid interface                     | $N\ m^{-1}$ |
| $\gamma_{sv}$        | Surface tension of solid-vapor interface                      | $N\ m^{-1}$ |
| $\delta$             | Dimensionless fiber spacing                                   |             |
| $\varepsilon$        | Aspect ratio of fiber                                         |             |
| $\eta_{de}$          | Deposition efficiency                                         |             |
| $\eta_{ac}$          | Aerodynamic collection efficiency                             |             |
| $\eta_{dr}$          | Drainage efficiency                                           |             |
| $\eta_a$             | Ratio between penetrating airflow and the unperturbed airflow |             |
| $\eta_b$             | Ratio between captured droplets and the challenge droplets    |             |
| $\theta$             | Contact angle                                                 |             |
| $\theta_r$           | Receding contact angle                                        |             |

|                 |                                               |                    |
|-----------------|-----------------------------------------------|--------------------|
| $\theta_a$      | Advancing contact angle                       |                    |
| $\theta_w$      | Wenzel contact angle                          |                    |
| $\theta_{CB}$   | Cassie-Baxter contact angle                   |                    |
| $\kappa$        | Film curvature                                | $\text{m}^{-1}$    |
| $\lambda$       | Dominating PRI Wavelength                     | $\text{m}$         |
| $\lambda_c$     | Critical PRI wavelength                       | $\text{m}$         |
| $\Lambda$       | Dimensionless PRI wavelength                  |                    |
| $\Lambda_{KHI}$ | Dimensionless KHI wavelength                  |                    |
| $\mu$           | viscosity of air                              | $\text{Pa s}$      |
| $\mu_w$         | viscosity of water                            | $\text{Pa s}$      |
| $\zeta$         | Radius of curvature                           | $\text{m}$         |
| $\rho$          | Density of air                                | $\text{kg m}^{-3}$ |
| $\rho_w$        | Density of water                              | $\text{kg m}^{-3}$ |
| $\tau_p$        | Timescale of PRI                              | $\text{s}$         |
| $\tau_{pc}$     | Timescale of PRI at a critical film thickness | $\text{s}$         |
| $\tau_{th}$     | Timescale of film thinning                    | $\text{s}$         |
| $\varphi$       | Dimensionless clogging size                   |                    |
| $\Phi$          | Dimensionless obstacle size                   |                    |
| $\Phi_{th}$     | Threshold dimensionless obstacle size         |                    |
| $\chi$          | Dimensionless fiber diameter                  |                    |
| $\omega$        | Dimensionless growth rate of perturbation     |                    |

## List of Abbreviations and Acronyms

| Notation | Term                                             |
|----------|--------------------------------------------------|
| AC       | Alternating current                              |
| BOAS     | Bead-on-a-string                                 |
| CREW     | Charge-reversed electro-jet writing              |
| DC       | Direct current                                   |
| DMAc     | N,N-dimethylacetamide                            |
| DMSO     | Dimethyl sulfoxide                               |
| KHI      | Kelvin-Helmholtz instability                     |
| NFES     | Near-field electrospinning                       |
| PAN      | Polyacrylonitrile                                |
| PDMS     | Polydimethylsiloxane                             |
| PEMA     | Poly(ethyl methacrylate)                         |
| POSS     | Polyhedral oligomeric silsesquioxane             |
| PTFE     | Polytetrafluoroethylene                          |
| PVDF     | polyvinylidene difluoride                        |
| PVDF-HFP | Poly(vinylidene fluoride-co-hexafluoropropylene) |
| PIV      | Particle image velocimetry                       |
| PRI      | Plateau-Rayleigh instability                     |
| ROW      | Rivulet-on-web                                   |
| RTI      | Rayleigh-Taylor instability                      |
| SEM      | Scanning electron microscopy                     |
| s.d.     | Standard deviation                               |
| STIV     | Space-time image velocimetry                     |
| TES      | Traditional electrospinning                      |

# Chapter 1 Introduction

## 1.1 Background

Water scarcity has become one of the greatest challenges faced by humanity in the twenty-first century. Population growth, climate change, water overuse, and water pollution are depleting the usable water resources [1]. Currently, 1 billion people do not have access to clean, piped water, and 41% of global population lives in water-stressed areas [2]. As regions struggle to cope with depleting freshwater resources, innovative solutions must be developed and deployed for mitigation.

Harvesting water from humid gases is an emerging approach to tackle the challenge of water scarcity. Humid gases, such as ambient air and combustion exhaust gas from industrial boilers and engines, usually contain large amounts of water vapor or droplets. For example, the water vapor content in atmosphere contributes to 3% of surface freshwater on earth, higher than the contribution of rivers and swamps [3]. In addition, the exhaust gas from coal-fired boilers of power industries generally contains 12% - 16% water content [4], which is usually discharged into the atmosphere and wasted. Therefore, harvesting water from the humid gases can help increase the available fresh water reserves on earth, while avoiding the waste of fresh water resources.

Various types of water harvesting technology have been developed over the last decade. Depending on the physical state of water molecules during the harvesting process, the harvesting technology can be categorized into fog harvesting, dew harvesting and absorption-based harvesting [5]. Specifically, the fog harvesting directly captures tiny water droplets drifting in airstreams such as ambient air [6] and industrial stack plumes [7]. The dew harvesting technique harvests the gaseous water vapors by condensation [4, 8, 9]. In addition, the absorption-based harvesting technique uses water absorbents to capture water molecules, then desorbs liquid water by temperature-swinging operations [1].

Among these techniques, fog harvesting is particularly beneficial in terms of the unique characteristics of low-energy intensity. In general, fog harvesting mainly relies on the process of mechanical impingement of droplets on obstacles [6, 10]. The impingement process requires minimal energy input other than the mechanical energy of the fog-laden airflow. In contrast, both dew and absorption-based harvesting requires the supply of coolant for condensation and desorption. However, the regeneration of the coolant requires external energy input [11].

Therefore, the fog harvesting technique is promising in areas where the power supply for cooling is limited.

The fog harvesting technique typically uses fog collectors to separate the airborne droplets from the airstream. As shown in Figure 1.1, a typical fog collector is based on a permeable structure which consists of solid obstacles and openings. The permeable collector allows a portion of airflow to pass through the openings, while the rest circumvent the collector due to the aerodynamic resistance. The fog droplets carried by the penetrating airflow (challenge droplets) can be captured by migrating across the air streamline and impinging on the solid surface of the obstacles [12]; the rest of the droplets escapes by passing through the opening or drifting along the deviated streamline of airflow due to the blocking of the obstacle. The captured fog droplets grow on the surface of the collector until they are sufficiently large to shed from the collector into a storage tank [5]. During the harvesting process, the surface properties and geometrical parameters of the collector structure determines the ability of the collector to capture droplets and shed collected water [12]. Therefore, the development of superior collector structures is necessary to achieve efficient fog harvesting.

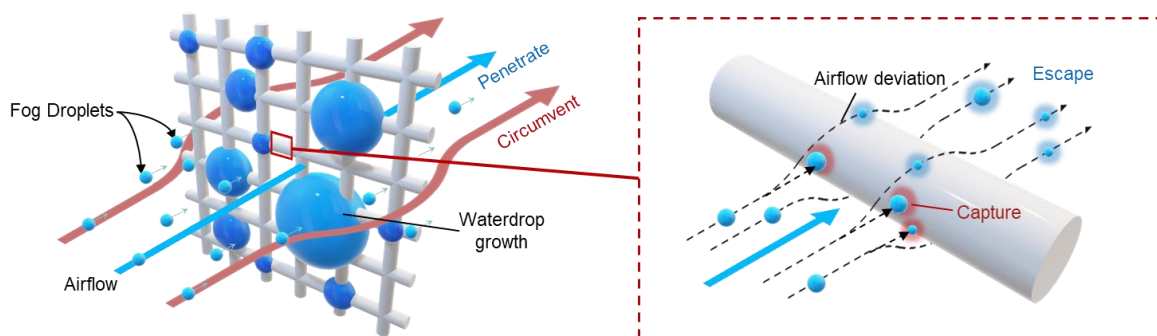


Figure 1.1. Schematic of the typical fog harvesting process on a permeable fog collector

## 1.2 Motivations and challenges

Fiber-based collectors with the structures of grids or meshes take up a substantial portion of fog collectors. As shown in Figure 1.2, the number of publications related to fog collectors generally increase from 2000 to 2024, and the fiber-based fog collector rises to take a portion of about 1/3 of total publications. The most widely used fiber-based collector is the Polyethylene-based Raschel mesh. Typically, polyethylene fibers with a typical diameter of 1 – 2 mm are weaved into a Raschel mesh with a rectangular shape [6, 10, 12]. The collector based on the Raschel mesh has a typical size of 4 m (height) × 12 m (width) and is usually placed upright against the droplet-laden airflow [13, 14]. Such collectors have been deployed

to coastal mountains and highlands with abundant fog resources and shown resistance to tearing at high windspeeds [14-16]. However, the Raschel mesh suffers from the low collection efficiency in the range of 5-10% at windspeeds less than  $2 \text{ m s}^{-1}$  [12, 14]. Therefore, efficient fiber-based collectors are desired to better harvest fog water.

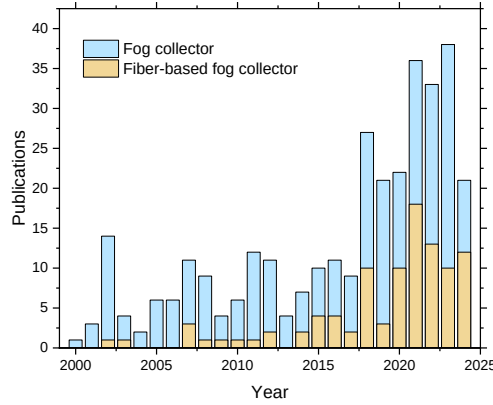


Figure 1.2. Record of publication from 2000 – 2024 for fog collectors and fiber-based fog collectors. The record data is obtained from Web of Science by searching the topics of “fog collector” and “fog collector mesh/grid/fiber”.

To develop efficient fog collectors, the fundamentals of fog-harvesting ability should be briefly reviewed. Generally, the ability can be described by water collection efficiency, which is defined by as the ratio between the flow of collected water per unit collector area and the unperturbed liquid water flux normal to the collector [17]. By definition, the efficiency is first determined by how many water droplets can impinge on the collector surface. Specifically, the droplets can escape from being captured by (a) circumventing the collector due to aerodynamic resistance, (b) passing through the openings of collector, and (c) drifting along air streamlines without the impingement due to the viscous drag of airflow [13, 17-19]. In addition, the efficiency also relies on how much captured water can reach the collection container, because the loss of captured fog water may occur due to evaporation and entrainment [13, 17, 19]. Furthermore, the captured droplets grow into large waterdrops before shed from the collector, which clogs the opening and reduces efficiency [20]. Overall, the collection efficiency has three contributing factors, which can be written as

$$E = \eta_{ac}\eta_{de}\eta_{dr} \quad (1)$$

$\eta_{ac}$  is the aerodynamic efficiency, indicating the fraction of droplets moving towards fibers.  $\eta_{de}$  is the deposition efficiency, indicating the fraction of droplets depositing on fibers.  $\eta_{dr}$  is the drainage efficiency, indicating the fraction of collected water reaching the container.

The aerodynamic efficiency is based on inviscid potential flow theory. As shown in Figure 1.3, the inviscid potential flow assumes no flow recirculation and negligible viscous effects to simplify the flow field [21]. As a result, the aerodynamic efficiency is determined by the ratio between the flow area  $A_1$  and  $A_2$ . This approach allows modeling aerodynamic efficiency with shade coefficient  $SC$  and pressure loss  $C_P$  of the collector.

$$\eta_{ac} = SC \cdot \frac{A_2}{A_1} = \frac{SC}{1 + \sqrt{C_P/C_0}} \quad (2)$$

Here,  $C_0$  is the drag coefficient of an impermeable plate, which is a constant for collectors with a fixed size [19]. The shade coefficient is the fraction of grid area covered by fibers, i.e.,  $SC = A_{\text{fiber}}/A_{\text{grid}}$ , which affects the pressure loss because more shaded area generates higher resistance [19]. Based on this model, the shade coefficient should be sufficiently large to capture droplets, and meanwhile sufficiently small to let airflow pass through. However, this model does not include the viscous effects. In practical situations of using thin fibers in low velocity airflows, the Reynolds number is small, which indicates that flow around fibers is dominated by viscosity. Therefore, the viscous effect should be considered for evaluating the efficiency.

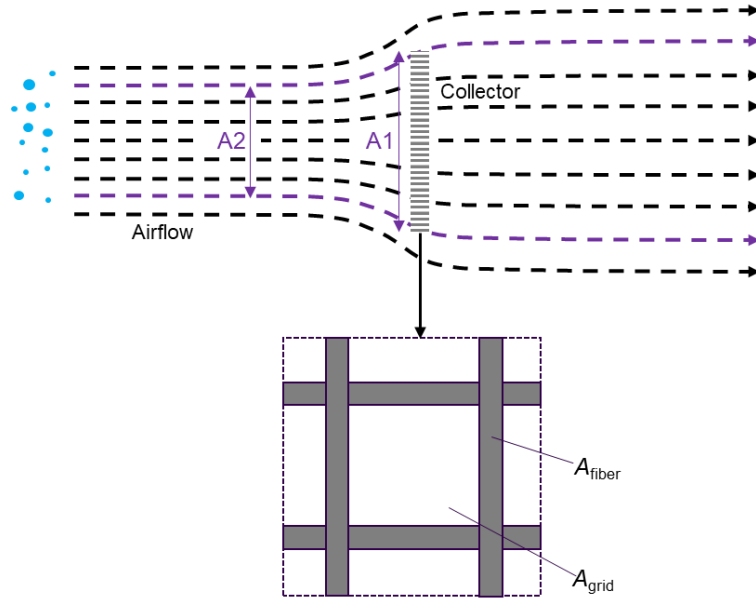


Figure 1.3. Schematics of aerodynamic efficiency and shade coefficient.

The deposition efficiency is based on droplet inertial impaction. As shown in Figure 1.4, droplet deposition involves multiple mechanisms, including diffusion, interception, impaction and electric attraction. Natural fog droplets are normally neutral with diameter in the range of 2 to 50  $\mu\text{m}$  [17, 22]. In this range, the inertial impaction dominates, which is characterized by the Stokes number  $Stk$  as follows:

$$Stk = \frac{\rho_w d_{fog}^2 u}{9\mu d_{fiber}}$$

Using the Stokes number can calculate deposition efficiency as follows:

$$\eta_{de} = \left( \frac{Stk}{Stk + \alpha} \right)^\beta \quad (3)$$

where  $\alpha$  and  $\beta$  are positive coefficients. This equation indicates that a thin fiber with a large  $Stk$  leads to high deposition efficiency. However, this model only considers bare fibers without the existence of waterdrops, which is unrealistic because the deposited fog water can form waterdrops to further influence the deposition. Therefore, a detailed investigation into droplet depositions on fibers with waterdrops should be conducted.

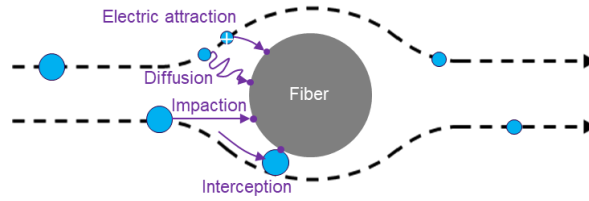


Figure 1.4. Schematics of droplet deposition mechanisms.

In practical situations, the waterdrops generally exist on fibers, which are formed by Plateau-Rayleigh instability (PRI). As shown in Figure 1.5, the deposited droplets form a water film around the fiber. This film is hydrodynamically unstable when subject to environmental perturbations [23]. These perturbations further develop to decompose the film into drops that are distanced by the dominating wavelength, which is known as PRI. Between the neighboring PRI drops, a thin precursor film exists to spontaneously transport water to nearby waterdrops, because the capillary pressure in PRI drop is lower than that in precursor films.

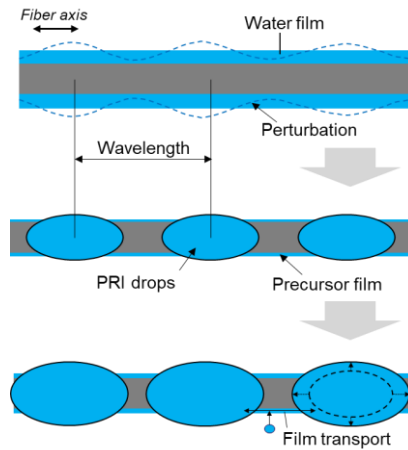


Figure 1.5. Schematics of Plateau-Rayleigh instability.

The waterdrop further clogs the collector to influence both aerodynamic and deposition efficiency. As shown in Figure 1.6, the clogging drops generate higher resistance to airflow, which drives airflow to circumvent the collector and brings negative influence on aerodynamic efficiency [20]. Also, the clogging waterdrops have a smaller Stokes number than bare fibers due to the increased obstacle size, which drives droplets to pass around without impaction [24]. In addition, the waterdrop increases the shade coefficient, which has a positive effect by providing more areas to capture droplets. However, this positive clogging effect has not been investigated, especially regarding its potential for efficient droplet capture.

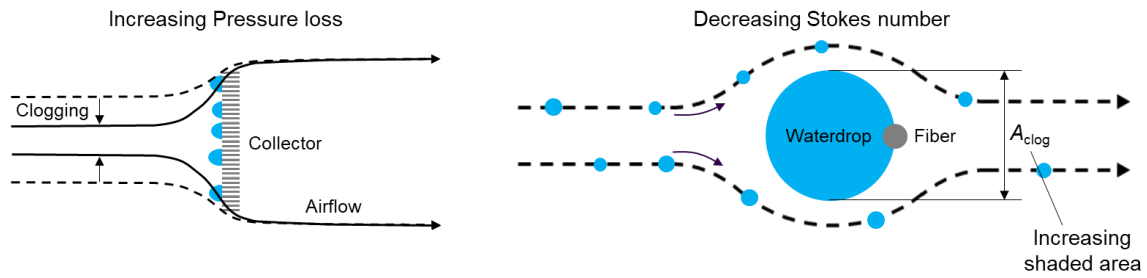


Figure 1.6. Schematics of clogging effects on fog harvesting.

Long-lasting waterdrop clogging is unfavorable because evaporation and re-entrainment may occur, which leads to the loss of fog water. To remove the water clogging, surfaces and structures of the collector have been modified with the ability of enhanced water transport. Among them, bionic structures inspired by natural life, such as spider silk [25-28], cactus [29-31], desert beetles [32, 33] and nepenthes [34, 35], have been an emerging research area because these structure can spontaneously transport water. For example, the spider silk with knot-joint structures generates unbalanced forces on contact lines, which leads to a net force to drive the waterdrop. However, the complex bionic structures are difficult to fabricate through large-scale fiber spinning techniques, which however is required for large-scale fog collectors [5]. Also, the drop-wise transport needs to overcome the pinning force, which limits the transport distance [36]. Therefore, finding a simple structure for long-distance transport is required for efficient fiber-based collectors.

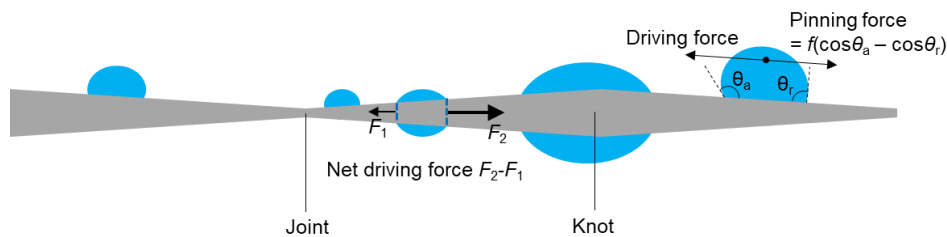


Figure 1.7. Schematics of spontaneous water transport on the spider-silk bionic structure.

Overall, fiber-based fog collectors have become a critical area of research due to their enhanced ability to capture droplets and transport water. However, the development of efficient collectors still faces the following limitations. First, the dominating viscous effects at small  $Re$  are not addressed in existing efficiency models. Understanding the viscous effect can help to establish a universal efficiency model, which is particularly useful for fog harvesting with low air velocities and thin-fiber structures. In addition, the positive effect of water clogging on collection efficiency remains unclear, thus requiring further understanding and utilization of this effect for enhanced droplet capture. Furthermore, the transport of water on thin fibers relies on creating complex bionic structures, which brings difficulty in fabrication and large-scale applications. This challenge raises demand for simple fiber structures with the ability of spontaneous water transport.

### 1.3 Research objectives

The objective of this thesis is to develop efficient fog collectors based on thin fibers with simple structures. Based on the introduced background, an efficient collector relies on both enhanced droplet capture and water transport, which requires a fundamental investigation of fog harvesting process. Therefore, the objective is achieved by several steps.

- First, the effects of fiber-grid structures on water collection efficiency should be understood, especially in the situation with low fiber Reynolds number and the existence of water clogging. This provides insights into the theories of fog harvesting and guidance to the collector design.
- Then, droplet capture on micro-fiber grids is studied to better understand the positive clogging effects on collection efficiency, allowing the optimization of the fiber-grid structure.
- Finally, the fiber with a simple ribbon-like shape is proposed with the ability to spontaneously transport water due to Plateau-Rayleigh instability with a long wavelength. A study of instability and fluid flow on fiber is carried out to understand the mechanism behind the water transport.

The research target is achieved by completing the following tasks.

- 1) Developing a multi-scale numerical model of fog harvesting process based on a fiber-grid structure.

- 2) Varying the parameters of fiber diameter, spacing and water clogging radius to study the effect of collector structure on water collection efficiency.
- 3) Comparing the model results to existing theories and design rubrics to identify the effects of viscosity and water clogging on collection efficiency.
- 4) Fabricating micro-fiber grids with geometric parameters for utilizing the positive clogging effect discovered in the modeling study.
- 5) Evaluating the collection efficiency of the fabricated thin-fiber grids.
- 6) Studying the mechanism behind the high collection efficiency in terms of the positive clogging effect.
- 7) Comparing the formation waterdrops on thin fibers with cylindrical and ribbon-like shapes due to Plateau-Rayleigh instability.
- 8) Visualizing the flow on ribbon-like fibers to study the characteristics of water transport.
- 9) Designing and fabricating a fiber-grid structure to transport water over the collector surface.

## 1.4 Thesis structures

Figure 1.8 shows the structure of this thesis. First, Chapter 1 presents the background of fog harvesting followed by introducing the current research trend of novel fog collectors. Noticeable gaps exist in terms of droplet capture and water transport for developing efficient fiber-based collectors. Therefore, this thesis is motivated to fill the gaps, which leads to better design of thin-fiber fog collectors.

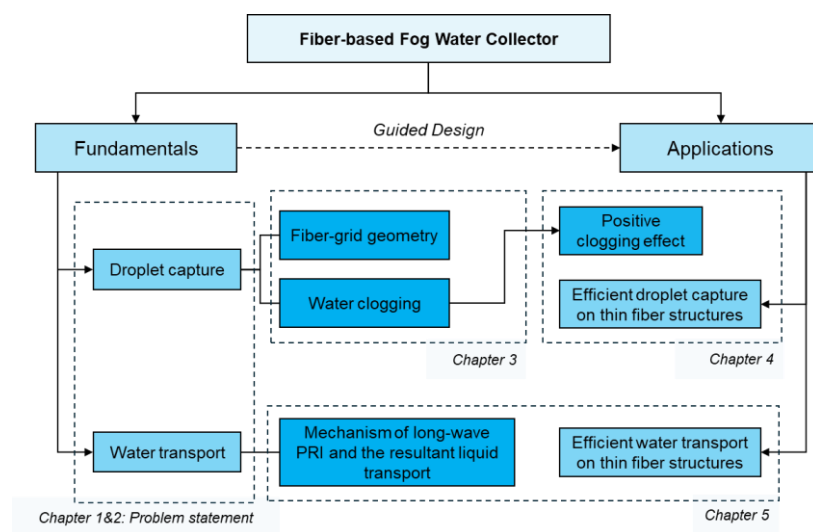


Figure 1.8. Schematic of the thesis structure.

Chapter 2 provides a thorough literature review to cover the fundamentals of fog harvesting and different design of fog collector structures. This chapter elaborates on how the knowledge gaps in Section 1.2 is identified for this thesis work, which is achieved by reviewing the state-of-the-art research progress and summarizing the missing aspects in terms of designing efficient fog collectors. In addition, the method used to prepare fibers in this thesis work, i.e, near-field electrospinning, is briefly reviewed for explaining the reasons of NFES used for fabricating fiber-based collectors.

Chapter 3 presents a multi-scale numerical study to simulate fog harvesting on fiber-grid collectors across a wide range of fiber diameters, spacing and clogging radius, in order to understand the effect of low Reynolds number and water clogging on collection efficiency. Fog harvesting is modelled at two length scales, i.e., collector scale and fiber scale. The two scales are coupled using coefficients representing aerodynamic resistance and droplet capture. The model is first validated with experimental data obtained from literature and this work. Then the validated model is used to study the impact of parameters, including fiber diameter, fiber spacing and clogging drop radius, on the water collection efficiency.

Chapter 4 studies the effects of waterdrop clogging on water collection efficiency, aiming to better understand and utilize the positive clogging effect on microfibers discovered in Chapter 3. Specifically, microfiber grids are fabricated with near-field electrospinning technique by processing the solution of PVDF-HFP into patterned fiber grids. Experimental fog collection test of the fabricated fiber grids is carried out to study the mechanism of positive clogging on micro-fiber grids. Then, the water collection efficiency is measured to evaluate whether the positive clogging effect can lead to a high collection efficiency.

Chapter 5 investigate the formation and transport of waterdrops on ribbon-like fibers based on long-wave Plateau-Rayleigh instability, which provides a feasible strategy of spontaneous and continuous water transport along designated path on fog collectors. The PRI wavelength is measured for cylindrical and ribbon-like fibers to study the mechanism behind the long-wave PRI on ribbon-like fibers. Water transport based on long-wave PRI is visualized to investigate the characteristics of the water transport. Then, a fiber-grid structure is designed to evaluate the feasibility of liquid transport across the collector surface.

Chapter 6 concludes this thesis and discusses the future directions for relevant research.

## Chapter 2 Literature Review\*

### 2.1 Basics of fog harvesting

Harvesting fog water starts with the generation of water droplets. In general, the condensation of water vapor leads to the formation of tiny droplets when the humid air is cooled below the water dewpoint. Those tiny water droplets tend to suspend in the air and drift with airflows, which is commonly observed in nature as fog, and in industry as plumes. Specifically, the size of natural fog follows a logarithmic distribution within the range of 2 – 50  $\mu\text{m}$  [17, 22]. In contrast, the industrial plumes, such as the cooling tower plume, can exhibit a bimodal size distribution within the range of 1 – 100  $\mu\text{m}$  [37].

The fog collector is a permeable structure that collects water droplets drifting with airflows. The design of the permeable structure usually affects the process of fog harvesting, which in general involves the following steps.

- a. The fog-laden airflow approaches the permeable collector and develops a flow field as follows. A portion of airflow penetrates the collector by passing through the openings, and the rest circumvents the collector due to the aerodynamic resistance of the collector.
- b. The challenge droplets carried by the penetrating airflow move towards the collector surface. Specifically, a portion of challenge droplets migrate across the streamline of the airflow and deposit on the obstacles; the rest escape through the collector openings without being captured.
- c. The captured droplets can spread on the fiber surface and form a thin water film. The thin film on a fiber is hydrodynamically unstable and can decompose into waterdrops when exposed to environmental perturbation.
- d. The waterdrops formed by instability can further grow larger to clog fiber openings. At worst scenario, the clogging waterdrops may bridge the neighboring fibers to fully clog the openings.
- e. The captured fog water is transported as drops or films from the collector surface to the collection container via gravity or other active transport methods.

The listed steps are usually affected by one or more parameters of collector structure and harvesting conditions, and eventually impact the collection efficiency. Therefore, this section

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\* The contents in this chapter relevant to near-field electrospinning have been published in *Materials Today Advances* 21: 100461.

extensively reviews the recent studies of preceding steps, in terms of their contribution to fog collector design, and discusses the knowledge gaps in designing efficient fog collectors.

### 2.1.1 Penetrating and circumventing airflow

The dominating factor determining the flow field around the collector is the aerodynamic resistance of the collector. In general, a collector with more openings and less obstacles usually have a lower resistance, which allows more airflow to penetrate the collector, and vice versa. On the other hand, the resistance diverts airflow to circumvent the collector, creating a shear layer between the penetrating and circumventing airflow. The shear layer triggers flow separation and recirculation in the wake region. Therefore, a relation between the aerodynamic resistance and fraction of penetrating airflow is important for understanding the effect of collector structure on the flow field.

Using an inviscid potential flow hypothesis, Rivera analytically derived the fraction of penetrating airflow in the form of airflow velocity as follows [21].

$$\frac{u_0}{u_p} = 1 + \sqrt{C_P/C_0} \quad (4)$$

where  $u_0$  is the velocity of the incoming airflow,  $u_p$  is the velocity of the airflow penetrating the grid,  $C_P$  is the pressure loss coefficient of the collector, and  $C_0$  is the drag coefficient of an impermeable plate with the same size of the collector ( $C_0 = 1.18-1.5$  for a rectangular collector). The pressure loss coefficient,  $C_P$ , is a function of the shade coefficient of the collector,  $SC$ , which is defined as follows.

$$SC = \frac{A_b}{A_c} \quad (5)$$

where  $A_b$  and  $A_c$  are the projected area of the obstacle and collector, respectively. Several theoretical or empirical models of  $C_P$  are available for different shapes of permeable structures. For example, the correlation of  $C_P$  and  $SC$  for wire and silk mesh is made by Idel'cik [38]:

$$\text{Wire mesh} \quad C_{P,wm} = 1.3SC + \left( \frac{SC}{1 - SC} \right)^2 \quad (6)$$

$$\text{Fiber mesh} \quad C_{P,fm} = 1.62C_{P,wm} \quad (7)$$

Eq. (6) and (7) both suggest that  $C_P$  monotonically increases with  $SC$ , as larger shaded area creates more resistance to airflows. Therefore, the fraction of the penetrating airflow mainly depends on the shade coefficient.

However, Rivera's model ignores the flow recirculation in the wake, which may cause deviations compared to practical situations. In fact, the recirculation caused by flow separation introduces a low-pressure zone downstream the collector, which generates a suction force due to pressure difference to draw in additional airflow. Such deviation has been noticed in existing numerical simulations [13]. The numerical results give the penetrating ratio twice that of Rivera's model, although the deviation is not explained in the reference. Therefore, Rivera's model is insufficient to accurately predict the ratio between the penetrating and circumventing airflow.

To better predict the ratio between the penetrating and circumventing airflow, more accurate models are required. Numerical modelling is a viable option, because it can accurately simulate the velocity and pressure profile in the wake, allowing the direct calculation of the penetrating airflow ratio [13]. Also, Steiros et al. corrected the inviscid potential flow hypothesis by introducing the wake suction to better predict the penetrating velocity, which is written as [39]

$$u^{*2} \left[ \frac{1}{(1 - SC)^2} - 1 \right] = \frac{4}{3} \left[ \frac{(1 - u^*)(2 + u^*)}{(2 - u^*)^2} + \frac{(1 - u^*)^3}{(2 - u^*)^2} \right] \quad (8)$$

where  $u^* = u_p/u_0$ . Eq. (8) provides an option for calculating the penetrating velocity without analyzing the actual flow structure downstream the collector. Therefore, the corrected analytical model or numerical models provides a viable approach for introducing the wake effect on penetrating airflows.

Overall, recent studies focus on penetrating and circumventing airflows generated by aerodynamic resistance. Several models have been developed to accurately predict the fraction of penetrating airflow. However, there is still a lack of studies since very few of them address the viscous effects on resistance. Indeed, the viscous effects are particularly important at low Reynolds numbers when using thin fibers or fiber structures to harvest fog at a low airflow velocity. Therefore, the viscous effect should be studied for efficient fiber-based collectors.

### **2.1.2 Migration and deposition of challenge droplets**

Droplet capture takes place when the challenge droplets can migrate to the surface of the obstacles and thus be captured. Therefore, it is important to know how the droplets drift with the airflow and impinge the obstacles.

A tiny droplet drifting with a velocity of  $\mathbf{v}$  in an airflow with a velocity of  $\mathbf{u}$  is normally subject to five types of forces – inertia, gravity, drag, Brownian force and electric force, which balances during the motion of the droplet.

$$\mathbf{F}_i + \mathbf{F}_g + \mathbf{F}_d + \mathbf{F}_b + \mathbf{F}_e = \mathbf{0} \quad (9)$$

The inertia, gravity, drag and electric forces can be described as follows.

$$\mathbf{F}_i = \frac{\pi}{6} \rho d^3 \mathbf{a} \quad (10)$$

$$\mathbf{F}_g = \frac{\pi}{6} \rho g d^3 \quad (11)$$

$$\mathbf{F}_d = 3\pi\mu d(\mathbf{u} - \mathbf{v}) \quad (12)$$

$$\mathbf{F}_e = \frac{\mathbf{E}q}{4\pi\epsilon_0} \quad (13)$$

where  $\rho$  and  $d$  are the density and diameter of the droplet,  $\mathbf{a}$  is the acceleration vector of the droplet,  $g$  gravitational constant,  $\mu$  the air viscosity,  $\mathbf{E}$  the electric field vector,  $q$  the net charge carried by the droplet, and  $\epsilon_0$  the permittivity of the air. In addition, the Brownian force is usually random in magnitude and direction and can be statistically expressed in terms of diffusivity using the Stokes-Einstein equation.

$$D_p = \frac{kT}{3\pi\mu d} \quad (14)$$

where  $k$  is Boltzmann constant, and  $T$  the air temperature. Hence, droplets with a small diameter drifting in hot air have high diffusivity and are subject to large Brownian forces. The Brownian force drives the droplet to diffuse in the direction opposite to the gradient of droplet concentration.

It should be noted that the preceding expressions for the drag force and Brownian force are based on the situation where the droplet is much larger than the mean free path of air molecules, which is also referred to as continuum regime [40]. This regime can be defined using a small Knudsen number ( $Kn \ll 1$ ), which is the ratio of gas mean free path  $\ell$  to droplet radius  $d/2$ .

$$Kn = \frac{2\ell}{d} \quad (15)$$

For small droplets ( $Kn \gg 1$ ), slipping between the gas and the droplet may occur and affect the drag and Brownian force via a non-zero slipping velocity at the interface between droplet and air. Therefore, the Cunningham correction factor  $C_c$  should be included for  $F_d$  and  $D_p$  to correct the slipping boundary as follows.

$$F_{d\_corr} = \frac{F_d}{C_c} \quad (16)$$

$$D_{p\_corr} = D_p C_c \quad (17)$$

The Cunningham correction factor can be determined by several mathematical correlations. The most widely used one is from Flagan and Seinfeld [41], written as follows .

$$C_c = \begin{cases} 1 + 1.257Kn & Kn < 0.001 \\ 1 + Kn \left[ 1.257 + 0.4 \exp\left(-\frac{1.1}{Kn}\right) \right] & 0.001 < Kn < 100 \\ 1 + 1.657Kn & Kn > 100 \end{cases} \quad (18)$$

The mathematical expressions for the forces reveal the following characteristics of droplet drifting. At a small droplet diameter  $d$ , the contribution of gravity to drifting trajectory normally vanishes compared to the drag and Brownian force, because  $F_g \propto d^3$ . For extremely small droplets, the contribution of drag also vanishes due to  $F_d \propto d$ , leaving the dominant factor of Brownian diffusion, where the diffusivity is inversely proportional to the droplet diameter. For fog harvesting process, the gravity contribution is normally ignored, because the droplet diameter is normally within the range of 1 – 100  $\mu\text{m}$ . Therefore, this review mainly discusses the contribution of inertia, Brownian force, and electric force.

The drifting droplet can migrate towards and then deposit on an obstacle immersed in the airflow. As shown in Figure 2.1a, the streamline of airflow is perturbed by the existence of the obstacle. As a result, a droplet drifting along the streamline with a velocity  $\mathbf{v} = \mathbf{u}_0$  experiences a drag force near the obstacle, which is caused by the diverted direction of airflow velocity  $\mathbf{u}$ . According to Eqs. (11)-(14), the drag force tends to keep the droplet moving along the curved streamline; however, other forces may drive the droplet to migrate across the streamline and impinge on the obstacle. Therefore, the deposition of droplets on obstacles is based on the deviation of droplet trajectory from the airflow streamline, which is achieved by the forces overcoming the drag.

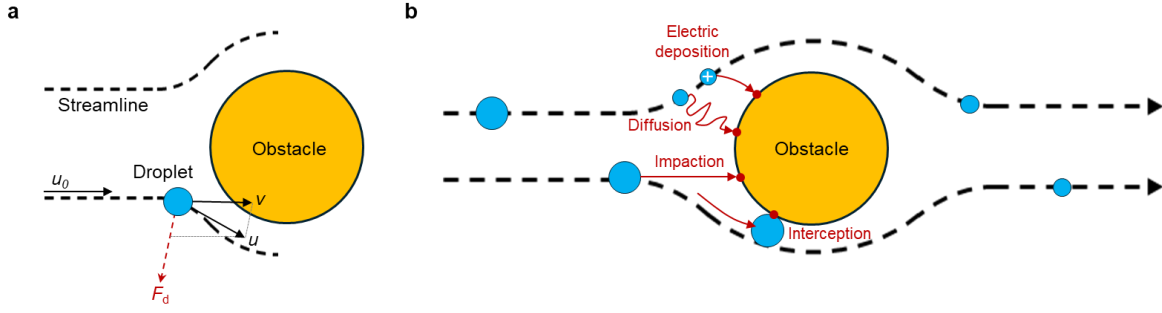


Figure 2.1. Schematic of droplet capture. (a) Perturbed streamline of airflow and resultant drag on the drifting droplet. (b) Four different mechanisms of droplet deposition on obstacles

Depending on the type of contributing force, four different mechanisms exist for droplet deposition, i.e., diffusion, interception, impaction, and electric deposition (see Figure 2.1b). Specifically, diffusion occurs for small particles subjected to Brownian force, where the low concentration of droplets around the obstacle (i.e., concentration boundary layer) drives the diffusion of droplet towards the obstacle [42]. In addition, interception takes place for droplets moving along the curved streamline due to the dominant drag, whereas the boundary of the droplet contacts the surface of the obstacle due to the non-negligible droplet diameter. Moreover, droplets with large inertia due to large diameter or high velocity tend to ballistically migrate across the streamlines, directly impacting the obstacle. Furthermore, droplets carrying electric charges can be attracted to the obstacle when an electric potential exists crossing the streamline.

The contribution of each mechanism to deposition is quantified by the deposition efficiency,  $\eta_{de}$ , which is defined as the ratio between deposited droplets and incoming droplets within the projection plane of the obstacle [19]. For different mechanisms, the deposition efficiency exhibits distinct dependency on parameters such as the droplet diameter, obstacle size, and airflow velocity. Here, previous studies of deposit efficiency for cylindrical obstacles are reviewed, because this thesis focuses on fiber-based collectors, and the fiber normally takes a cylindrical shape.

The efficiency due to diffusion can be estimated using the following equation [42]

$$\eta_{de-diff} = 3.68A^{1/3}Pe^{-2/3} \quad (19)$$

where  $A$  is the Kuwabara coefficient approximated as  $A = [2(2 - \ln Re_b)]^{-1}$  with  $Re_b$  as the obstacle Reynolds number, and  $Pe$  is the Peclet number calculated as  $Pe = ud/D_p$ . Eq. (19) indicates that the deposition efficiency due to diffusion is only crucial for small droplet diameters ( $< 0.1 \mu m$ ).

For typical fog droplet diameters ( $2 < d < 50 \mu\text{m}$ ) at frequent airflow velocities ( $2\text{-}6 \text{ m s}^{-1}$ ), the deposition efficiency due to diffusion is less than 1% [19].

The interception mechanism becomes important when the droplet diameter is sufficiently large, the deposition efficiency can be estimated as [42]

$$\eta_{de-int} = 2A \left( \frac{d}{d_b} \right)^2 \quad (20)$$

where  $d_b$  is the diameter of the cylindrical obstacle. The equation indicates that the contribution of interception mechanism is sensitive to the relative size difference between the droplet and the obstacle. For a droplet-laden airflow with  $d = 10 \mu\text{m}$  and  $u = 2 \text{ m s}^{-1}$ , increasing the obstacle diameter from  $50 \mu\text{m}$  to  $100 \mu\text{m}$  sharply decreases the efficiency from 90% to zero.

Droplets directly impacting the obstacles usually have larger inertia compared to the air drag, which can be characterized by the Stokes number

$$Stk = \frac{\rho_w d^2 u}{9\mu d_b} \quad (21)$$

where  $\rho_w$  is the mass density of droplets. Based on the Stokes number, several models have been developed for deposition efficiency due to impaction. Those developed models mainly take two types of mathematical forms as follows

$$\eta_{de-imp} = \left( \frac{Stk}{Stk + \alpha} \right)^\beta \quad (22)$$

$$\eta_{de-imp} = \frac{Stk^3}{Stk^3 + \alpha Stk^2 + \beta Stk + \gamma} \quad (23)$$

where  $\alpha, \beta, \gamma$  are numerical constants. Both forms indicate that the efficiency monotonically increases with the Stokes number, and the monotonical relationship follows a sigmoidal curve. The shape of the sigmoidal curve is determined by the specific value of the numerical constants, which are provided in Table 2.1.

Table 2.1. Numerical constants of equations for calculating deposition efficiency due to impaction

| Reference                       | Expression | $\alpha$ | $\beta$ | $\gamma$ |
|---------------------------------|------------|----------|---------|----------|
| Langmuir & Blodgett (1946) [43] | Eq. (22)   | $\pi/2$  | 1       | n/a      |
| Chamberlain (1967) [44]         | Eq. (22)   | 0.6      | 3.2     | n/a      |
| Belot & Gauthier (1975) [45]    | Eq. (22)   | 0.1      | 1.9     | n/a      |

|                                    |          |       |       |        |
|------------------------------------|----------|-------|-------|--------|
| Thorne et al. (1982) [46]          | Eq. (22) | 5     | 1.05  | n/a    |
| Landahl & Hermann (1949) [47]      | Eq. (23) | 0.77  | 0     | 0.22   |
| Davidson & Friedlander (1978) [48] | Eq. (23) | 0.753 | 2.796 | -0.202 |

Notably, the impaction mechanism is the most important contributor to the overall deposition efficiency for fog harvesting [19], because the typical droplets diameter, obstacle size and airflow velocity generally gives a large Stokes number. For example, a droplet-laden airflow with  $d = 10 \mu\text{m}$  and  $u = 2 \text{ m s}^{-1}$  passing around an obstacle with a diameter in a range of  $10 \mu\text{m}$  to  $1 \text{ mm}$  gives a relatively large Stokes number in the range of  $1.23 - 123$ , leading to a high deposition efficiency of  $44\% - 99\%$  using the model from Langmuir & Blodgett.

Electric deposition is a special mechanism that occurs for charged droplets drifting in an existing electric field. For the specific situation of electrical fog harvesting, the electric field is generated between a grounded collector and droplets that are charged by an emitter electrode. The interactions between the airflow, droplets and electric field complicate obtaining an explicit form of deposition efficiency [40]. To reduce the complexity, Damak et al employed a dimensionless number  $Ke$  to describe the contribution of electric forces as follows [49].

$$Ke = \frac{L}{d_b} \frac{1}{\mu u L^2 / 2 \varepsilon d V^2 + 1} \quad (24)$$

where  $V$  is the voltage applied on the emitter electrode,  $L$  the distance between two electrodes. The authors also reported linear relationships between  $Ke$  and the deposition efficiency due to electric deposition. The linear relation  $\eta_{\text{de-ed}} = 0.26Ke$  holds for a single cylindrical collector, and  $\eta_{\text{de-ed}} = 0.1Ke$  for mesh collectors with multiple cylinders. Therefore, the electric deposition efficiency mainly depends on the applied voltage on emitter electrode and the inter-electrode distance.

Overall, the deposition of droplets takes place through the mechanisms of diffusion, interception, impaction and electric deposition. Among these mechanisms, impaction is the most important contributor for fog harvesting. However, the deposition efficiency significantly decreases when the droplet diameter and airflow velocity are reduced, requiring a small obstacle size to better capture droplets through impaction.

Notably, the majority of the reviewed deposition models are borrowed from filtration theories, where the obstacles are treated as bare particle collectors. However, fog collectors exhibit a difference in terms of growing waterdrop on obstacles. The existence of waterdrops

normally affect the flow field and thus the deposition. A study on fibers wetted by drops is reported by Labbé et al. [24]; however, the study focuses on separate fibers instead of grid or mesh structures that are usually used for fog harvesting. Therefore, the deposition efficiency should be further studied for fiber grids or meshes in the practical situation of fog harvesting.

### 2.1.3 Water spreading and hydrodynamic instabilities

The droplets deposited on a dry obstacle normally cannot retain their spherical shape. Once contacting the obstacle, the droplet spreads and wets the obstacle surface. Usually, a contact angle is formed between the water-vapor and water-solid interface, and the angle is determined by the wettability of the obstacle surface and described by Young's equation [50].

$$\gamma_{sv} = \gamma_{ls} + \gamma_{lv} \cos \theta \quad (25)$$

where  $\gamma$  is the surface tensions of the liquid-vapor (lv), liquid-solid (ls), and solid-vapor (sv) interfaces, and  $\theta$  is the contact angle. In addition, the deformable liquid-vapor interface is constrained by the surface tension of water, attempting to sustain a spherical shape [51]. As a result, the deposited droplet takes a shape close to a semi-spherical cap, which develops a larger cross-section area compared to the drifting droplet.

The deposition and spreading of numerous fog droplets lead to the formation of a water film. During the process of fog harvesting, deposition and spreading takes place at the entire surface of the obstacle. Meanwhile, the spreading droplets in close distances can merge with each other into a film. According to Dalili et al. [52], dense droplet deposition and spreading results in the formation of a continuous liquid film when inter-droplet distance is less than 0.7 times the spreading diameter of droplets. For a typical fog condition with airflow velocity of 2 m s<sup>-1</sup> volumetric mean droplet diameter of 10 μm and liquid water content of 0.1 g m<sup>-3</sup> [17], more than 200 droplets deposit on 1 mm<sup>2</sup> surface of the obstacle in 1 second. The deposition of droplets is much denser than the criterion set by Dalili et al. Therefore, the deposited droplets develop into a water film covering the fiber in a short period of time.

As the continuous deposition of droplets gradually increases the thickness of water film, the film becomes hydrodynamically unstable and tends to decompose into drops. In general, this hydrodynamic instability is due to the leveling of the liquid-vapor interface of the film in response to environmental perturbations [53]. Specifically, the perturbation of interface is a series of sinusoidal modes with various wavelengths and infinitesimal magnitude. Among them, several modes may result in a decrease in the energy of the system, causing the perturbation magnitude to increase further and thus become unstable. Of all the unstable modes, the most

rapidly growing mode eventually wins out and dominates the instability, manifesting a dominating wavelength that can be measured as the distance between drops [54].

Plateau-Rayleigh instability is most commonly observed for fiber-based collectors. Fibers have highly curved surfaces, which provides a positive curvature for the deposited water film, generating a positive capillary pressure in water phases. Once perturbed, the film adopts the shape of alternating crest and trough, where the radius of curvature,  $r$ , at the trough is larger than that at the crest by two times of the perturbation magnitude [53]. The resultant capillary pressure,  $p$ , at the trough is larger compared to the crest according to the Laplace equation  $p = \gamma/r$ , thus driving a capillary flow from the trough to the crest. The flow eventually drains the trough film and decomposes the film into a necklace of drops (*see* Figure 2.2a), which is known as the Plateau-Rayleigh instability (PRI) [54]. Using linear stability analysis, the dominating wavelength is calculated as follows [23].

$$\lambda = 2\pi\sqrt{2}a \quad (26)$$

where  $a$  is fiber radius. This specific wavelength corresponds to the fastest growing mode with a characteristic growth time as follows [23].

$$\tau = \frac{12\mu_w a^4}{\gamma h^3} \quad (27)$$

where  $h$  is the thickness of the water film. Eq. (26) and (27) indicates that the dominating mode of PRI depends on the curvature of fiber surface, and the growth rate increases with the film thickness. Notably, these two equations are applicable to situations where the film thickness is much smaller than the fiber radius ( $h \ll a$ ), and the liquid-solid interface is endowed with a non-slip condition. Conversely, for thick films, the thickness  $h$  also contributes to the wavelength, thus  $a$  in Eq. (26) should be replaced by  $h+a$  [54]. In addition, a slip condition tends to reduce the characteristic growth time for an enhanced PRI [54], and the slippery surface allows the liquid to flow further for a longer wavelength [55].

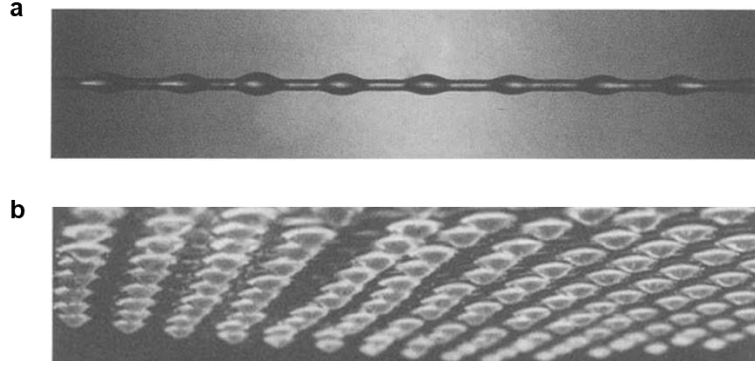


Figure 2.2. Photos of drops formed by hydrodynamic instabilities. (a) Plateau-Rayleigh instability on a fiber. (b) Rayleigh-Taylor instability on a plane [53]

However, PRI is mainly responsible for the drop formation on a single fiber. For a collector with a structure of fiber network, drops tend to form at the intersections of fibers, because the intersection provides a larger surface area with lower surface energy compared to the separated fibers [56-58]. Indeed, this situation can be treated as “artificial” PRI with the wave crests fixed at the intersection, because the intersection always tries to aggregate more water on its large surface.

In addition, Rayleigh-Taylor instability (RTI) can occur if the fog collector has a horizontal planar structure. The water film suspended on the horizontal plane is subjected to both gravity and surface tension. Gravity tends to distort the film by transporting water downward, while the surface tension resists any tendency to increase the surface area [53]. Similar to PRI, the perturbed film has alternating crests and troughs. However, RTI has a different mechanism of surface distortion: large gravity at the crest overcomes the surface tension to further aggregate water from the trough, forming hanging drops under the plane (see Figure 2.2b). Using linear stability analysis, the dominating wavelength is calculated as follows [53].

$$\lambda = 2\pi \sqrt{\frac{2\gamma}{\rho_w g}} \quad (28)$$

This wavelength has the fastest growing mode with the following characteristic growth time.

$$\tau = \frac{12\gamma\mu_w}{\rho_w^2 g^2 h^3} \quad (29)$$

Eq. (26) indicates that the dominating mode of RTI depends on the capillary length of water  $l_{cp} = (\gamma/\rho_w g)^{1/2}$ , which is a constant as 2.7 mm for water at room temperature, leading to a constant

wavelength as 24.1 mm. In addition, the growth rate of RTI increases with the film thickness, similar to the growth rate of PRI.

Overall, the deposited fog droplets form a water film on the surface of the collector. Under the influence of environmental perturbation, the film develops hydrodynamic instabilities, including PRI on fibers and RTI on planes. However, it is noticed that current studies of PRI are focused on cylindrical fiber, and fibers with other types of geometries are not widely studied. Therefore, different shapes of fibers, such as flattened ribbon-like fibers, should be studied to evaluate the influence of fiber shape on waterdrop formation.

#### 2.1.4 Water clogging and transport

The water drops formed by instability usually adhere to the collector surface, hindering the capture of fog droplets. The drops clog the opening areas, increasing the resistance of the collector [12, 20]. As a result, more airflow tends to circumvent the collector instead of penetrating, reducing the chance of droplet deposition. In addition, the formed drops usually have a larger size compared to the obstacle, which lowers the deposition efficiency through droplet impaction [24, 59]. Furthermore, the waterdrops hanging on collectors are subject to evaporation and re-entrainment, which causes water loss and decreases efficiency. Therefore, severe clogging should be avoided by transporting the collected water out of the collector.

For conventional collectors without the ability to actively transport water, the size of clogging drop continuously grows until gravity overcomes the adhesion, allowing the drop to detach from the surface. Therefore, the detachment force is important for removing clogging. Tadmor et al. used the Young-Dupre equation to describe the detachment force as follows [60].

$$F = 2\pi r_w \gamma (1 + \cos \theta) \quad (30)$$

where  $r_w$  is the wetting radius. For a drop with a fixed volume, a small contact angle increases the wetting radius, which leads to increased force to detach the drop. Therefore, the hydrophobic surface with larger contact angle and smaller wetting radius is beneficial for drop detachment. However, Eq. (30) can only be applied to planar surfaces, and the variation of wetting radius and drop deformation is not considered. In addition, Farhan et al. modeled the detachment force for drop hanging on a fiber [61]. The model includes the effect of actual wetting radius and the drop deformation on detachment force. Consequently, the model satisfactorily predicts the force for fibers with contact angle larger than 20°. Moreover, Park et al. derived a useful expression of the critical radius of a drop detaching from a vertically placed fiber mesh [62].

$$r = \sqrt{\frac{12\gamma(\cos \theta_r - \cos \theta_a)}{\pi\rho_w g B(3 + B^2)}} \quad (31)$$

where  $\theta_r$  and  $\theta_a$  are the receding and advancing contact angle on the mesh, and coefficient  $B$  is calculated as  $(1-\cos\theta)/\sin\theta$ . Eq. (31) indicates that a small critical radius requires the contact angle hysteresis term,  $\cos\theta_r - \cos\theta_a$ , to be sufficiently small, which can be achieved by using a non-sticky hydrophobic surface (lotus surface) [63] or a liquid-infused surface [64].

In addition, clogging can also exist as water bridge between fibers for mesh or grid collectors with fine structures. Similar to waterdrop clogging, bridge clogging usually brings negative influence on resistance and deposition efficiency [59]. Even worse, the bridge can spread over the collector surface to form a connected clogging pattern, which completely blocks the opening and appears as an impermeable plate [62]. To cope with the bridge clogging, a large opening size is normally required to destabilize the formed water bridge, which can be characterized using the capillary length  $l_{cp}$ , which is calculated as  $(\gamma/\rho_w g)^{1/2}$  [65]. Specifically, for a grid structure with mesh opening larger than  $l_{cp}$ , the liquid bridge is unstable and tends to break up; however, the fine grids with opening much smaller than  $l_{cp}$  normally develops a bridge clogging spreading over the grid [62]. Therefore, the formation of bridge clogging imposes limitations on the opening size of grid structures.

To solve the problem of water clogging, novel fog collectors have been developed using structures that can actively transport water. The water transport ability is usually achieved by using surfaces that can generate driving forces on deposited water [34, 66-72]. Depending on the types of the surface, the mechanisms of water transport are reviewed as follows.

Surfaces with varying roughness can create contact angle difference along the roughness gradient, which drives the transport of waterdrops [73]. A rough surface has a different apparent contact angle compared to the intrinsic contact angle based on Young's equation. The apparent contact angle is based on the Wenzel and Cassie-Baxter wetting state, which indicates whether the drop can fully wet the rough surface without trapping air pockets (*see* Figure 2.3).

$$\text{Wenzel} \quad \cos \theta_w = r \cos \theta \quad (32)$$

$$\text{Cassie-Baxter} \quad \cos \theta_{CB} = f_1 \cos \theta - f_2 \quad (33)$$

where  $r$  is the ratio between the effective contact area and its planar projection along the surface,  $f_1$  and  $f_2$  are the fraction of solid-liquid and vapor-liquid interfacial areas to the planar projection of drop bottom, and  $\theta$  is the intrinsic contact angle. The Wenzel and Cassie-Baxter models

indicate that the surface-roughness related parameters,  $r$  and  $f$ , affect the static contact angle, wettability, and surface free energy. Accordingly, the gradient of these parameters leads to that of the contact angle of the drop is different along the gradient [74]. As a result, an imbalanced force is generated on the contact line of the drop, which can be expressed in the following form by integrating the force along the contact line.

$$F_D = \pi r_w^2 \gamma \left( \frac{d \cos \theta_a}{dx} \right) \quad (34)$$

where  $\theta_a$  is the apparent contact angle calculated by the Wenzel or CB model, and  $x$  the length along the gradient. Eq. (34) indicates the contact angle difference generates a driving force that is regulated by the wetting radius of the drop. Therefore, roughness-driven transport usually requires a large roughness gradient and a large wetting radius.

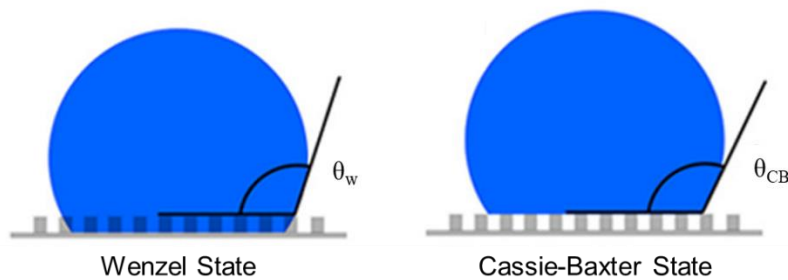


Figure 2.3. Schematics of Wenzel and Cassie-Baxter state of a drop wetting a rough surface [75].

In addition, conical structures can transport water from the tip of the cone to the base. The driving force is generated by the capillary pressure gradient due to varying curvature from the tip to the base, which can be expressed as [28, 76]

$$F_D = \int_{a_2}^{a_1} \frac{2\gamma}{(a + r_w)^2} \sin \alpha \, dx \quad (35)$$

where  $a$  is the local radius of the conical structure,  $a_1$  and  $a_2$  are the local radius at the two opposite sides of the drop, and  $\alpha$  is the half-apex angle of the cone. It is found that the value of  $F_D$  increases with the apex angle and the difference between  $a_1$  and  $a_2$ . Therefore, conical structures with more tapered surfaces can better transport waterdrops.

Furthermore, several structures can transport water in a film-wise way. Generally, achieving film-wise liquid transport is difficult because the deposited water tends to develop hydrodynamic instabilities and form waterdrops, as discussed in Section 2.1.3. Therefore, film-wise transport is only possible when the transport capability can overwhelm the instability onset by maintaining a small film thickness. However, natural living creatures have developed

the unique structure for film-wise water transport over the long history of evolution. Among them, pitcher plants are the masters of water transport. For example, the peristome surface of *nepenthes alata* has a grooved structure consisting of duckbill-shaped microcavities, allowing the water transport uphill over the internal surface of its pitchers [35]. In addition, *Sarracenia* has a trichome structure of longitudinal ribs with different heights, by which microchannels with hierarchical widths are developed [34]. These two structures allow ultra-fast water transport by a two-step mechanism: the water wets the microchannels and forms a precursor liquid film, followed by film-wise water transport by slipping upon the film.

Overall, water clogging is formed by the adhesion of deposited droplets to the collectors. To avoid the formation of clogging, well designed grid structures with hydrophobic surfaces are required. On other hand, structures with varying roughness, conical shape and bionic microchannels can actively transport liquid, reducing the clogging formation on collector. However, a fundamental study on the effect of water clogging on droplet deposition is missing, although most existing studies state that the water clogging is solely negative for fog harvesting. In addition, film-wise water transport is achieved by creating complex bionic structures, which are limited in terms of designing fog collectors for practical use. Therefore, it is desired to investigate the effect of water clogging on fog harvesting and explore the simple structures with the ability to actively transport water.

## 2.2 Efficiency of fiber-based collectors and design rubrics

Based on the preceding process of fog harvesting, the relationship between the structure of fiber-based collectors and harvesting performance can be further shaped. Generally, the performance can be quantified using the water collection efficiency,  $E$ , which depends on three important contributors. First, the overall efficiency  $E$  first relies on the ratio between the penetrating airflow towards the solid fibers to the overall airflow, a factor known as the aerodynamic collection efficiency,  $\eta_{ac}$  [21]. Rivera's theoretical model introduced in Section 2.1.1 is conventionally used for evaluating  $\eta_{ac}$ , which is described as follows.

$$\eta_{ac} = \frac{SC}{1 + \sqrt{C_P/C_0}} \quad (36)$$

Using this expression, a maximum  $\eta_{ac}$  can be obtained at an optimized  $SC$  of 0.5-0.6 based on Idel'cik's correlation of  $C_P$  and  $SC$  for fiber grids [21].

Second, the efficiency  $E$  also depends on the deposition efficiency,  $\eta_{de}$ . For fiber-based collectors, Langmuir's model of droplet deposition on a cylinder is widely used to describe  $\eta_{cap}$  as follows [43].

$$\eta_{de} = \begin{cases} 0 & (Stk < 0.125) \\ 0.466(\log_{10} 8Stk)^2 & (0.125 < Stk < 1.1) \\ Stk/(Stk + \pi/2) & (Stk > 1.1) \end{cases} \quad (37)$$

Eq. (37) indicate that using a grid with a smaller fiber diameter increases the Stokes number, leading to an elevated  $\eta_{de}$  of fog droplets and thus a higher overall efficiency.

Third, the ratio of water reaching the water collection container to the captured fog droplets, i.e., the draining efficiency  $\eta_{dr}$ , also affects the overall efficiency  $E$ . The airflow exerts drag forces on the collected water, which may overcome the adhesion between water and fiber grid and re-entrain the collected waterdrops. In addition, water evaporation also causes the loss of efficiency. Consequently, re-entrainment and evaporation prevents the collected waterdrops from reaching the container, thus reducing the overall collection efficiency.

Together, these three main efficiency contributors constitute the overall collection efficiency written as follows.

$$E = \eta_{ac}\eta_{de}\eta_{dr} \quad (38)$$

As a result, the efficiency  $E$  is affected by multiple factors in a complex manner, including airflow velocity, fog droplet size, grid geometry, and fiber surface wettability. Park et al. [12] rewrote the overall efficiency for square wire meshes in an explicit mathematical form by (a) expressing  $SC$  with  $\delta = l_{sp}/d_{fiber}$ , where  $l_{sp}$  is fiber spacing and (b) neglecting the influence of drainage efficiency, as follows.

$$E = \eta_{ac}\eta_{de} = \frac{1}{1 + \sqrt{C_P/C_0}} \frac{2\delta - 1}{\delta^2} \frac{Stk}{Stk + \pi/2} \quad (39)$$

The equation shapes a well-known design rubric for fog collector geometries, where a thin-fiber grid with a  $\delta$  in the range of 3-4 gives the highest water collection efficiency. In addition, they pointed out that reducing the fiber diameter to a micrometer level causes waterdrop clogging [12], which reduces the overall efficiency due to the loss of permeability and increase of pressure loss  $C_P$ . The conclusion leads to another rubric for thin-fiber collector design, which is to remove the clogging waterdrops before they cover grid openings.

Notably, the existing theoretical models and design rubrics are based on a limited investigation of fog harvesting process. First, Rivera's model assumes a potential flow field around the collector. However, the permeable structure may cause flow separation and recirculation downstream of the collector [39], which creates a discrepancy against the assumption. In addition, Langmuir's model of droplet deposition on cylinders is valid for single fibers or fiber grids with large spacings. However, reducing fiber diameter and spacing causes interactions between fibers due to boundary layer effects [77], thus affecting droplet deposition. Furthermore, the design rubric for removing clogging is based on the presumption that water clogging reduces collection efficiency. In contrast, several studies show that clogging may enhance water collection at certain conditions [62, 78]. Therefore, investigating fog harvesting by fiber grids with different fiber geometries and clogging sizes is necessary to extend existing theories and shape new design rubrics.

## **2.3 Advances in structure design for efficient fog collectors**

Based on the basics of fog harvesting and collection efficiency models reviewed in Section 2.1-2.2, the structure of fog collectors can be categorized into two types: coarse structures with obstacle size larger than 1 mm, and fine structures with obstacle size smaller than 1 mm. This categorization is based on the respective advantages of the two structures, where coarse structures are less likely to develop water clogging on collector surface, and fine structures are more likely to capture droplets by providing a higher deposition efficiency.

Recent advances on fog collector design focus on overcoming the respective disadvantages of the coarse and fine structure, which are reviewed separately as follows.

### **2.3.1 Coarse structures**

Novel collectors with coarse structure have the disadvantage of low deposition efficiency, although less water clogging is formed on the collector surface. For example, at the typical fog condition with airflow velocity of  $2 \text{ m s}^{-1}$  and droplet diameter of  $10 \text{ }\mu\text{m}$ , the coarse structure with obstacle size larger than 1 mm have a small Stokes number less than 1.23, which generates a low deposition efficiency of 44%. Considering that the resistance of the collector reduces the penetrating airflow, the aerodynamic efficiency is limited to less than 30% even when with an optimal SC of 0.5-0.6 [21]. Together, the water collection efficiency is less than 13.2%. Therefore, enhancing the droplet deposition is required for efficient collectors with coarse structures.

Enhancing depositions can be achieved by introducing centrifugal forces to mitigate the airflow deviation caused by the blocking of the obstacles. For example, Li et al. reported a vortex-assisted fog harvesting using collectors with pyramidal openings. The structure generates vortices inside the opening. Tiny droplets entrained into the vortex tend to move towards the vortex cores, because the drag force of the airflow acts as the centripetal force to trap the droplets. The trapped droplets agglomerate and grow to larger droplets, which generates a large centrifugal force that cannot be balanced by the air drag. As a result, inertia force ejects the agglomerated droplets to the collector surface and captures the droplets. Based on the enhanced deposition of droplets, the structure can effectively capture the droplets at a low airflow velocity of  $0.8 \text{ m s}^{-1}$  with a collection efficiency of 16.1%, which is twice that of the Raschel mesh. Therefore, vortex-assisted fog harvesting can improve the water collection efficiency by modifying the deposition of droplets.

In addition, introducing electric forces to attract droplets on collectors can also enhance the deposition. For example, Damak et al. introduced electric forces on droplets using a harvesting system consisting of an emitter and a collector electrode [49], which is similar to the electrostatic precipitator used for particle separation. Specifically, the emitter electrode is used to charge the fog droplets, and the collector electrode with a large diameter of 1.88 mm is grounded with zero electric potential. The charged droplets are subject to the electric field created by the electrodes, which drives the droplets to migrate towards the grounded collectors. Consequently, the directional migration leads to enhanced deposition droplets, including those that are not drifting towards the collector. The resultant collection efficiency is hundreds of times that of neutral droplets, depending on the applied voltage on the emitter electrode.

Based on the enhanced deposition due to electrical forces, Jiang et al. designed an electrostatic fog collector consisting of vertical metallic wires [79]. The wires are used as the discharge, repelling and collection electrodes to generate electrical forces on droplets, and the collection electrodes have a fairly large diameter of 7 mm. As a result, they obtained a nearly perfect water collection efficiency of  $> 90\%$ . Therefore, the introduction of electrical forces can greatly improve the collection efficiency, even with collectors of coarse structures.

### **2.3.2 Fine structures**

Collectors with coarse structure suffer from the efficiency loss of water clogging, although the small size of obstacle allows a high deposition efficiency. For example, Park et al. reported that the polyolefin fiber mesh with a diameter of 0.9 mm exhibits a low water collection efficiency

of less than 2% due to the severely clogged mesh opening. In contrast, the mesh coated with POSS-PEMA increases the collection efficiency to 5%, because the hydrophobic coating reduces the formation of water clogging. Moreover, further reducing the fiber diameter of the coated mesh to 0.35 mm increases the collection efficiency to 10%. Therefore, efficient collectors with fine structures need to reduce water clogging.

Reducing water clogging can be achieved by using structures that reduce the adhesion between the water drop and collector surface. For example, Shi et al. developed a fog harp collector with vertically aligned fibers of 0.25 mm diameter [20]. Compared to a mesh structure, the absence of horizontal fibers in fog harp decreases the pinning force acting on waterdrops, thus reducing the adhesion. As a result, the waterdrops are more likely to drip along the vertical fibers under gravity, which suppresses the formation of water clogging. The suppressed clogging leads to a collection efficiency three times higher than that of square grids. In addition, Kowalski et al. optimized the structure of the fog harp by adjusting the fiber diameters, spacing and material [80]. As a result, the PTFE coated stainless steel fibers with 0.25 mm diameter and 0.5 mm spacing gives the highest collection efficiency of 17%, which is obtained at a test condition of  $1.4 \text{ m s}^{-1}$  airflow velocity and  $18 \text{ }\mu\text{m}$  average droplet diameter. Therefore, reducing the adhesion between the collector and waterdrops can effectively increase the collection efficiency.

Also, the structures that can actively transport water are beneficial for reducing water clogging. The active transport ability is based on the mechanisms reviewed in Section 2.1.4. However, recent studies focus on employing bionic structures that include one or more mechanisms, thus enhancing the collection efficiency in multiple ways.

Cactus spine is one of the most studied structures with a feature of the conical structure. It has a hierarchical microstructure of grooves and bards on the spine, driving the directional transport of droplets due to the gradients in capillary pressure and contact angle [31]. Inspired by the cactus spine, Bai *et al.* produced a biomimetic spine structure with hierarchical grooves using electrospun fibers and used it for fog collection [81]. They reported a water collection rate of  $0.3 \text{ }\mu\text{L/min}$  for each spine with a  $360 \text{ }\mu\text{m/s}$  moving speed.

Spider silk is capable of directional liquid transport due to the combination of roughness gradient and conical structure. Spider silk has alternating conical on micron-scale and roughness variation on nanoscale [28]. This multiscale morphology generates gradients in both capillary pressure and contact angle. The gradients facilitate directional transport of droplets

towards the spindle knots, enhancing droplet coalescence and water collection. Researchers have reported a bead-on-a-string (BOAS) artificial structure of fiber materials to mimic spider silk [25-28, 82]. For example, Du *et al.* fabricated a fiber-radiate membrane based on electrospun fibers with BOAS structures. The water collection efficiency on the membrane with BOAS structures is three times that without the BOAS structure [83].

The mechanisms of water transport on pitcher plants have also inspired the structural design of fog collectors. For example, Li *et al.* use 3D printing technique to produce a peristome-mimetic surface [72]. They harvested 40 mL of water in 2 hours with a fog flow of  $5.6 \times 10^{-2}$  g/s, corresponding to a collection rate of  $6.1 \times 10^{-3}$  g/cm<sup>2</sup>/s, which is higher than the artificial structure of spider silk and cactus spine.

To sum up, the advances in structural design for fog collectors focus on overcoming the limitations of collection efficiency. For coarse structures, external forces are introduced to enhance the deposition efficiencies. For fine structures, reducing water clogging is the key to enhancing water collection efficiency. However, these reviewed structures have significant shortcomings for practical applications. For example, the requirement of high voltage for electrostatic collectors is difficult to achieve in practical use due to the dangerous electrical shock in moist environments. In addition, the hydrophobic chemical coating normally ages in an ambient environment, which limits the lifespan of the fog collector. Furthermore, creating complex structures for better capture and water transport is limited in terms of fabrication and long-term use. Therefore, simple structures without coating and electricity input are required for safe, reliable and efficient fog harvesting.

## 2.4 Near-field Electrospinning

A novel fiber spinning technique, i.e., near-field electrospinning (NFES), is used in this thesis work to fabricate thin fibers and fiber grids. This technique uses electrical forces to draw solidified fibers from liquid polymer solutions, allowing the continuous spinning of fibers with various polymeric materials and different sizes. In addition, NFES is capable of depositing fibers in a programmable pattern by the mechanical translation of fiber collector electrodes. This ability has been utilized to create 2D and 3D fibrous structures for broad applications. Therefore, NFES is a powerful tool for preparing lab-scale samples of fiber-based structures, which is promising in enhancing droplet capture and water transport by creating different fiber grid structures.

This section reviews the basics of NFES technique and the methods of precisely creating 2D and 3D structures, aiming to provide insights into the fabrication of fibers and fiber grids that are suitable for harvesting fog water.

### 2.4.1 Introduction

An electrified jet goes through two stages: straight jetting and random whipping [84]. The formation of straight jetting originates from the deformation of a charged pendant drop into a conical shape, which is referred to as Taylor cone, at a critical voltage when the electric force balances the surface tension. Then the electric force streams a straight jet from the Taylor cone once overcoming the surface tension of the pendant drop [85, 86]. On the other hand, the random whipping instability onsets when the jet continuously thins to so that the viscosity and surface tension cannot stabilize Coulomb repulsions between jet segments [87, 88]. These two stages have been commonly observed in electrohydrodynamic processes, including electrospinning and electrospraying [84, 89, 90].

Electrospinning arises from the two-stage jetting and becomes a technology for the fabrication of nanofibers. Figure 2.4a illustrates the major components of a typical electrospinning setup, including a high-voltage power supply, a feeding device, a metallic needle spinneret, and a grounded collector [91]. The feeding device delivers polymer solutions to a metallic needle and forms a charged pendant drop. The high voltage applied on the needle develops the pendant drop into Taylor cone, straight jet, and drastic whipping jet. The whipping motion continuously stretches and thins the jet, while the evaporation of solvent leads to the solidification of the jet into fibers [89]. As a result, electrospinning can be used to fabricate nanofibers [89].

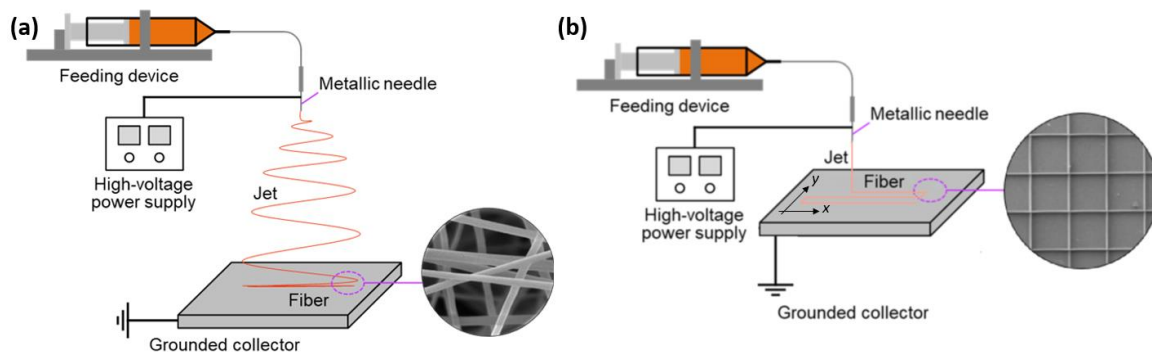


Figure 2.4. Schematics of typical setups of electrospinning. (a) Conventional electrospinning [91]. (b) Near-field electrospinning.

However, the random whipping motion results in the inability to obtain patterned fibers by electrospinning [92]. Electrospinning usually deposits fibers as mats because of the

randomly stacked fibers result from the whipping motion. The collector can be a plate or a rotating drum [93], and modifying the distribution of electric field [94, 95] can control the pattern of fibers. However, it is difficult to precisely pattern the fibers by conventional electrospinning.

Near-field electrospinning tackles the preceding challenge by orderly deposit fibers using the straight jetting segment. For example, Sun et al. [92] produced patterned fibers with reduced randomness by controlling the trajectory of the collector with the setup shown in Figure 2.4b. They used 0.5-3 mm tip-collector distance and a minimum voltage of 600 V to drive the straight jet, and they used a programmable X-Y stage to drive the collector and to control the position of fibers deposition.

Orderly deposition of fibers allows NFES to fabricate 2D and 3D structures. Simple 2D patterns include parallel lines [96, 97], coils [98, 99], waves [100, 101], triangles [102] and grids [103], and complex 2D patterns include letters and graphs [104, 105]. The 3D structures include vertically stacked fibers layer-by-layer [106], which allows the fabrication of the structures of walls [107], boxes [108], pillars [109-111] and other complex shapes [110, 112].

The 2D and 3D structures fabricated by NFES have various engineering applications. For example, the aligned patterns of piezoelectric PVDF fibers can harvest mechanical energy from the environment [113-120]. In addition, the complex 2D patterns facilitate the fabrication of the flexible electronics such as transistors [121-124] and transparent electrodes [122, 123, 125, 126]. Furthermore, the 3D fiber structures are widely used as biomedical scaffold because of their high surface area, interconnecting pores, and ability to control cell growth [108, 127-136].

Regardless of the structure, the fibers fabricated with NFES usually contain residual charges because of the low electrical conductivity of the polymer. The net charges dissipate both during flight and after deposition on the collector [107, 137]. However, the charge cannot quickly dissipate completely because of the limited conductivity of the solidified polymer fibers [107]. This leaves a considerable residual charge in deposited fibers, which may impair the NFES process.

How the residual charge impairs the NFES for 2D and 3D structures has been reported in the literature. For example, Zheng et al. reported that the residual charge generates repulsive forces on jet/nanofiber, resulting in jet oscillations and random fiber patterns [138]. Park et al. also reported that the repulsion hinders the formation of 3D fiber structures through layer-by-

layer deposition [107]. Most earlier studies on NFES have mainly focused on removing rather than using the residual charge.

Referring to the objectives of this research project, the following content summarizes methods to enhance the capability of NFES to create 2D and 3D structures. The fabrication of fibrous structures by NFES inspires the lab-scale preparation of fiber-based fog collectors in this thesis study.

## 2.4.2 Fabricating 2D/3D structures

This section reviews the methods of NFES for fabricating 2D and 3D structures. The following three terms are defined to quantify the capability of NFES fabrication:

- **Fidelity:** Fidelity is the consistency of the generated pattern compared to the designed one, which indicates the ability of NFES to place fibers along the target path. Fidelity loss is common to patterns with curvy lines and sharp corners [104]. Figure 2.5a illustrates the improvement on fidelity from the left to the right image by reducing the randomness from the whipping [139].
- **Resolution:** Resolution is the width of the deposited fiber or pattern; reducing the lateral size of the fiber improves the resolution [140]. For example, Figure 2.5b shows the resolution of a NFES, where the fiber diameter changes with the applied voltage [139].
- **Aspect ratio:** An aspect ratio is the ratio between the height and the width of a fabricated 3D structure, which describes the ability of NFES to deposit fibers layer by layer. Figure 2.5c shows the aspect ratio of a nanowall structure as the deposited fibers increase from 60 to 80 layers [107].

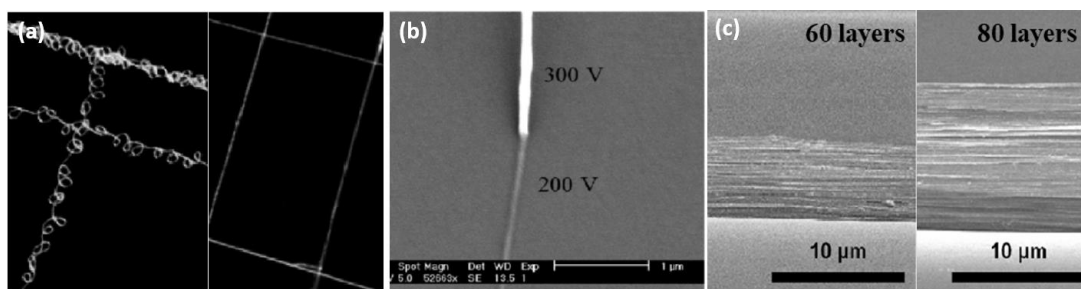


Figure 2.5. Three factors for evaluating the NFES capability to fabricate 2D and 3D structures. (a) Fidelity improvement from left to right figure by modulating the collector speed [139]. (b) Resolution variation by altering the voltage [139]. (c) 3D nanowall structures of different aspect ratios with 60 and 80 layers of fibers [107].

The methods to enhance the preceding capabilities include four categories, i.e., jet initiation control, jet-collector interaction modulation, instability suppression, and residual

charge removal. The following introduces the progress in each category and their enhancement in NFES capabilities.

#### *Jet initiation control*

The resolution of NFES is limited and requires improved control of jet initiation. It is determined by the diameter of fibers, which is usually larger than that by TES because of less stretching and evaporation[140]. Consequently, fabricating nanofibers needs a technique to initiate a thin jet [92]. Therefore, controlled jet-initiation in NFES is necessary to producing nanoscale fibers for precise 2D and 3D structures. Initial jet size can be controlled by 1) spinnerets with varied sizes, 2) voltage below the critical value, and 3) perturbation of the pendant drop surface at a subcritical voltage. They are introduced as follows.

First, using spinnerets with varied sizes can control the initial jet size. For example, Sun et al. used an 25  $\mu\text{m}$  thin solid needle as the spinneret to reduce the diameter of the jet and produced patterned nanofibers with diameters below 100-nm [92]. However, their method cannot deposit fibers continuously. In addition, using an ultrathin hollow needle increases the risk of clogging [89].

Second, using a voltage below the critical value, i.e., a subcritical voltage, in NEFS produces thin jets and fibers. For example, Lee et al. and Liashenko et al. fabricated 180-nm wide nanofiber-walls using a two-step voltage maneuver, i.e., a high voltage to overcome the surface tension on the pendant drop, followed by a low voltage to maintain the jet and reduce the size of the fibers [106]. Li et al. also used a stage initiator at a voltage of 50 V to initiate jet with the increased local electric field, followed by maintaining a thin jetting with reduced electric field when moving the spinneret away from the initiator [99].

Third, the perturbation of the pendant drop surface at a subcritical voltage helps initiate a thin jet. For example, Chang et al. initiated thin jets by a manual poke-and-draw method [140]. For starters, they maintained a subcritical voltage of 600 V between the needle and the collector to prevent the formation of Taylor cone or jet. Next, they used a tungsten tip of 1  $\mu\text{m}$  in diameter to poke inside the pendant drop and rapidly pulled away, which helped the liquid to overcome the surface tension and initiate a stable thin jet. This method, known as “mechanical drawing”, has been proven effective in producing fibers down to 16.2 nm in diameter [139].

#### *Jet-collector relative speed minimization*

The relative speed between the jet and the collector creates drag or impact between the jet and the collector, which affects the fidelity of fiber patterning. Bu et al. investigated the impact and drag while moving the collector at different speeds [141]. They found that the jet buckles at 50 mm/s as a result of the impaction between the jet and the collector, while the jet appears as a stable catenary because of the strong drag when the collector moved at 200 mm/s; see Figure 2.6a. Shin et al. also found maintaining a minimal relative speed improved the fidelity [104].

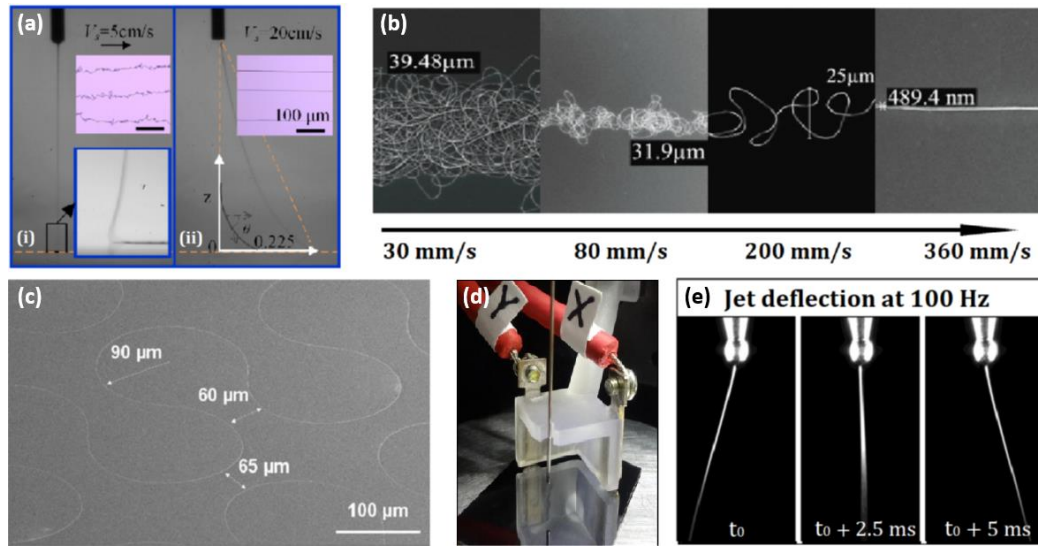


Figure 2.6. Modulation of relative impact speed between the jet and the collector. (a) The forms of the jet at different collector speed [141]. (b) Evolvement of fiber morphology with increasing collector speed from 30 to 360 mm/s [138]. (c) Curved pattern produced by modulating the jetting velocity [104]. (d) Photo of the device for creating the secondary electric field for jet deflection [142]. (e) Electrostatic deflection of jet at frequency of 100 Hz generated by wave signals from a function generator [142].

The first approach to minimizing the relative speed is to control the collector speed. For example, Zheng et al. controlled the collector speed to reduce the randomness of fiber deposition [138]. They reported that the jet bent and oscillated during deposition when the collector moved at a speed lower than that of the jet. Conversely, they suppressed the oscillation and reduced the width of the deposited pattern from  $39.48 \mu\text{m}$  to  $489.4 \text{ nm}$  by increasing the collector speed from 30 mm/s to 360 mm/s (see Figure 2.6b).

Regulating the jet speed, by varying the applied voltage and the working distance, also helps minimize the relative speed. For example, Shin et al. reported that low voltages and long distances helped generate low jet velocities by reducing the electric field strength [104]. They regulated the jet speed to 5 mm/s, by keeping a voltage of 400 V and a working distance of 0.5 mm, and created a micro-pattern with a radius of curvature of  $90 \mu\text{m}$  and a fiber spacing of  $60\text{--}65 \mu\text{m}$ ; see Figure 2.6c.

In addition, the relative speed can be minimized by adding an electric field normal to the jet axis. The normal electric field deflected the jet [96, 101, 142, 143] to accelerate the jet. This approach increases the fidelity when producing patterns with sharp edges or small radii of curvature [144]. For example, Liashenko et al. deflected the jet in a 2-D plane using two electrodes perpendicular to each other (see Figure 2.6d, e) to generate a secondary electric field [100]. The corresponding jet acceleration could reach up to  $10^6 \text{ m/s}^2$ , which is four orders of magnitude larger than that by the mechanical X-Y stage. Using this method, they produced continuous 2D patterns such as sawtooth and circles, as well as non-continuous patterns with a lateral size smaller than 2 mm [142]. Then, they extended the method to ultrafast fabrication of 3D structures, layer by layer, with a speed of 2000 layers/second, owing to the large deflection velocity up to 500 mm/s [142].

#### *Suppression of whipping instability*

Successful suppression of whipping instability can produce structures with high fidelity and large height-to-width aspect ratios. Suppressed whipping instability improves the fidelity by accurately placing fibers along the target trajectory rather than bending them away [145]. It also allows the defect-free layer-by-layer fiber deposition, improving the aspect ratio of 3D structure [112, 146]. Recent advances in whipping suppression are reviewed as follows.

Reducing voltage can effectively suppress the onset of whipping instability. For example, Chang et al. used a voltage of 600 V to suppress whipping onset [140]. They found that the fidelity of patterns improved by the suppression of whipping, allowing ordered deposition of fibers in grid and triangular patterns with controlled geometry; see Figure 2.7a. Bisht et al. also used a voltage in the range of 200-600 V and a working distance of 1 mm to suppress whipping onset [139]. They found that the whipping instability was suppressed with a voltage below 300 V. Therefore, low-voltage NFES favors the precise patterning with whipping suppression.

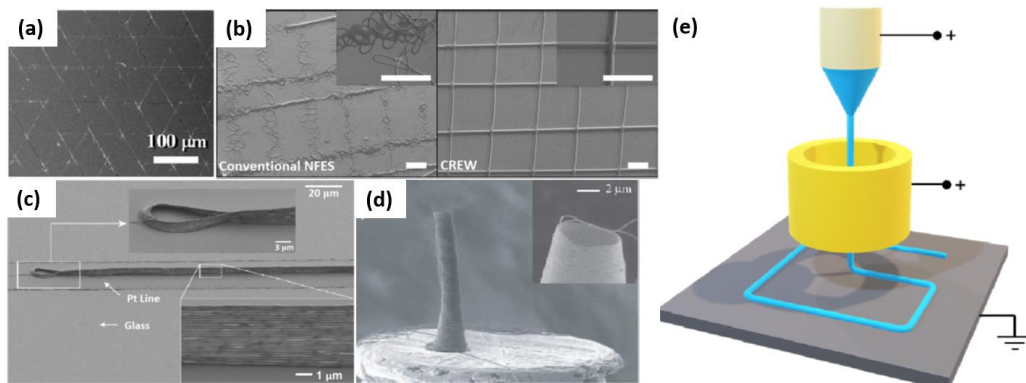


Figure 2.7. Electric field manipulation for whipping elimination. (a) SEM image of a triangular pattern fabricated by NFES using a low voltage of 600 V [140]. (b) SEM images of patterns fabricated by conventional NFES and CREW [112]. (c) 3D nanowall created by layer-by-layer deposition through an electric field focused onto a thin Pt line electrode [106]. (d) 3D nanopottery structure fabricated by tip-guided NFES system [109]. (e) Schematic diagram of jet focusing using an electrostatic lens.

Reversing the polarity of the electrodes can also suppress the onset of whipping instability. For example, Moon et al. developed a charge-reversed electro-jet writing (CREW) system by reversing the polarity of the electrodes in a traditional NFES setup [112], which suppressed the whipping instability by reducing the net charge in the jet. They attributed the reduced charge density to the lowered mobilities of positive ions compared to electrons. The reduced charge density weakens Coulomb repulsion, suppressing whipping onset. Figure 2.7b shows the high-fidelity pattern due to the suppressed whipping in CREW compared to conventional NFES under the same operation condition.

In addition, electric field focusing enhances axial stretching and suppresses whipping onset by generating axial attractions that converge towards the focusing point [106, 147, 148]. For example, Lee et al. used a 20- $\mu\text{m}$  wide patterned platinum electrode to focus electric field and successfully created a 3D structure of more than 300 layers of fibers (see Figure 2.7c) [106]. Kim et al. also used a stationary sharp metal tip to attract fibers to self-assemble into a hollow nanopottery (see Figure 2.7d) by a carefully controlled buckling process [109]. Furthermore, Zheng et al. used a sharp metal tip as the collecting electrode and placed a silicon wafer between the spinneret and the tip as a fiber collector, which is attached to a moving X-Y stage. They fabricated 3D structures through layer-by-layer stacking of up to 80 fibers, as a result of suppressed whipping due to electric field focusing [148].

Moreover, configuring a secondary electrode can suppress the onset of whipping. For example, Jordahl et al. configured an hollow cylindrical electrode surrounding the jet, which is charged with the same polarity as the jet [149], as seen in Figure 2.7e. The electrode creates a potential well around the jet, in which the lateral whipping is quickly eliminated by maintaining minimum energy. Such forced focusing of the jet is effective in creating complex patterns and defect-free 3D structures.

#### *Residual charge removal*

The enhancement of residual charges dissipation improves the capability of NFES in terms of fidelity and aspect ratio. Residual charge removal suppresses the Coulomb repulsion between the jet and the fibers, placing the fibers along the target trajectory with a high fidelity. On the other hand, the weakened charge repulsion reduces defects in layer-by-layer deposition,

improving the aspect ratio of 3D structures. Three methods to dissipate the charge are summarized as follows.

Driving the electrohydrodynamic jet with an alternating-current (AC), instead of direct-current (DC) electric field, enables the neutralization of charges among the deposited fiber segments [150]. For example, Zheng et al. [151] and Martinez-Prieto et al. [152] found that the AC induced charge neutralization and reduced net charge density in fibers. They used the AC setup to create fiber patterns of polylines and circles on non-conductive substances of PDMS and polyimide (see Figure 2.8a) [152], which is challenging to a conventional NFES setup. Therefore, the AC field NFES can neutralize residual charge and improve the ability of NFES to 2D patterns.

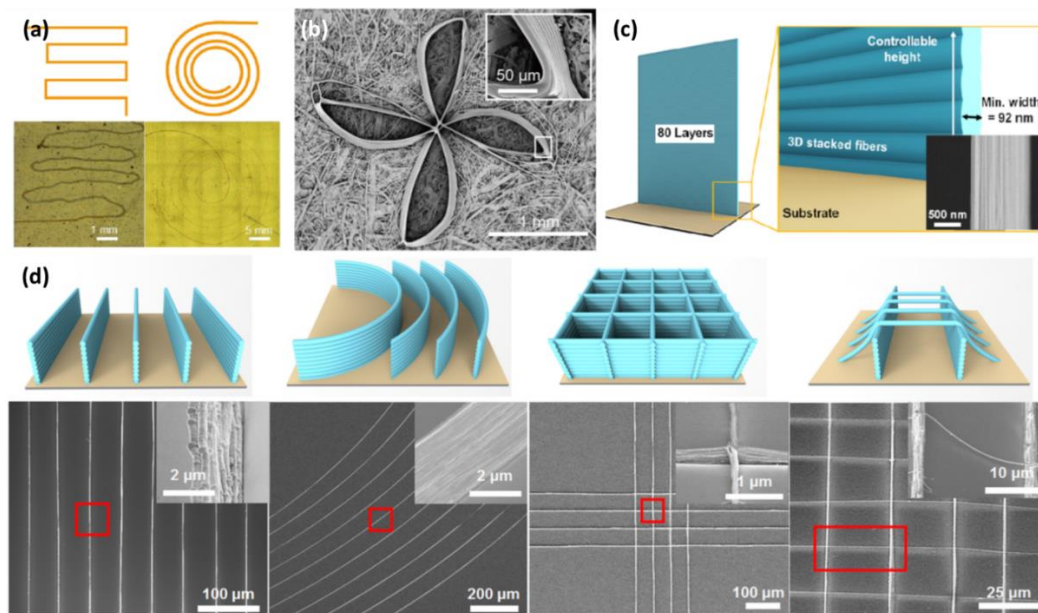


Figure 2.8. Methods for residual charge removal. (a) Patterning on insulated substrates of PDMS and polyimide [152] (b) Complex 3D flower structure fabricated using paper collector [110]. (c) Nanowall structure with a fiber diameter of 92 nm and an aspect ratio of 72, fabricated with the addition of NaCl salt to dissipate residual charge [107]. (d) Other 3D structure fabricated with the addition of NaCl [107].

The diffusion of residual charge from the deposited fibers to the conductive collector can also enhance the charge removal. For example, Luo et al. used paper as collectors to enhance the residual charge diffusion [110]. They found that the residual solvent in fibers due to incomplete evaporation spontaneously carries residual charge and infiltrates into the paper. To solve this problem, they successfully fabricated a nanowall structure with an aspect ratio of 50 using the paper collector [110]. Furthermore, they created complicated 3D structures, such as circular cone and floral structures, on the paper collector as shown in Figure 2.8b. Therefore,

the enhanced charge diffusion reduces residual charges and enhances the ability of NFES to fabricate 3D structures.

Alternatively, increasing the electrical conductivity of deposited fibers facilitates the removal of residual charge. For example, Park et al. added sodium chloride into the polymer solution to increase the electrical conductivity of fibers because it facilitated the discharge between the collector and the fibers [107]. Along with enhanced discharging, the increased conductivity connects the deposited fibers to the collector electrode, which forms a local electric pole to focus the electric field and attract subsequent deposition. Consequently, they observed a self-aligned, layer-by-layer stacking of fibers assembling into a nanowall structure with 80 layers of nanofibers; all fibers have a diameter of 92 nm (*see* Figure 2.8c) [107]. Using this method, they also fabricated more 3D structures, such as curved walls, lattices, and suspended fibers, with high aspect ratios, as shown in Figure 2.8d.

## 2.5 Knowledge gaps and research opportunities

The knowledge gaps for efficient collector design identified in Section 2.1-2.3 are summarized here for discussion.

- a. The viscous effects on aerodynamic resistance and collection efficiency
- b. The effect of waterdrop clogging on droplet deposition and collection efficiency, especially the positive clogging effect
- c. The structural design of fog collectors with high collection efficiency by utilizing the positive clogging effect
- d. PRI characteristics on non-cylindrical fibers and the resultant waterdrop formation
- e. Fog collectors with simple structures for fast water transport

To fill the gaps denoted by *a* and *b*, the collection efficiency, resistance, and droplet deposition of fiber-based collectors with different collector geometries and clogging situations should be evaluated. Numerical modeling provides a viable approach to simulate these variables as a function of collector geometry. Therefore, this thesis starts with a multi-scale modelling of fog harvesting using fiber grids, aiming to investigate the viscous and clogging effects on fog harvesting process. This part of work is completed in Chapter 3.

Continuing from the modeling study, the positive clogging effect due to specific collector geometries should be further investigated by experimental methods. The experimental study can provide insights of droplet deposition and collection efficiency in practical situations,

where the clogging waterdrops dynamically grow and shed and are difficult to simulate by numerical methods. In addition, it is desired to evaluate whether the positive clogging effect can enhance the collection efficiency compared to other reported fog collectors, which serves the purpose of filling the knowledge gap denoted by  $c$ . Using the NFES technique with the ability of precise fiber patterning [153], the fabrication of desired collector is possible, allowing the evaluation of collection efficiency of the fabricated collectors. This part of work is completed in Chapter 4.

For the gap denoted by  $d$ , this thesis experimentally investigates the characteristics of PRI on fibers with different shapes of cross section. Specifically, the PRI wavelength of cylindrical fibers and ribbon-like fibers are compared to evaluating the influence of surface curvature on PRI development. In addition, water transport is possible leveraging the precursor liquid film due to PRI. Water transport on ribbon-likes is investigated through experiments, which fills the gap denoted by  $e$ . This part of work is completed in Chapter 5.

## Chapter 3 Multi-scale Modeling of Fog Harvesting Using Thin-fiber Grids\*

### 3.1 Introduction

Current geometrical design rubrics for efficient fog collectors are based on the theory of potential flow and droplet deposition. For example, Rivera uses the potential flow theory to model fog water collection efficiency, stating that a projected area fraction of solid fibers in the range of 0.5-0.6 allows more challenge droplets to pass through the collector and migrate towards fibers [21]. The droplets are captured by fibers through diffusion, interception and impaction, among which impaction is the dominate mechanism due to the relatively large droplet diameter of 2-50  $\mu\text{m}$  [17, 19]. Multiple models of impaction are used to describe the efficiency of fog droplets captured by solid fibers, indicating that thin fibers can more effectively capture droplets because of larger Stokes numbers compared to thick fibers [19]. Overall, using a thin-fiber grid with a proper projected area fraction maximizes the water collection efficiency.

On the other hand, water clogging on the fog collector generally imposes a negative impact on collection efficiency. Waterdrops on the grid clog grid openings and elevate pressure loss over the grid. This leads to more airflow circumventing the collector, resulting in a loss of efficiency [12]. In addition, waterdrops distort the local airflow field which causes more droplets to circumvent the fiber grid instead of impacting the fibers [59]. Therefore, the novel design of fog collectors usually involves features of water transport to avoid clogging, such as harp-style grids [20, 80], biomimetic fibers [26, 27, 154], and superhydrophobic surfaces [155, 156].

Recent research progresses towards using thin fibers ( $d_{\text{fiber}} < 1000 \mu\text{m}$ ) or fiber-like structures to better harvest fog water at a low airflow velocity around  $1 \text{ m s}^{-1}$ . Figure 3.1a summarizes the studies related to fog harvesting between 2010 - 2024 according to the diameter of fibers and airflow velocity. The capped lines indicate the range of velocities and diameters used in the studies. Notably, most studies focus on low airflow velocities around  $1 \text{ m s}^{-1}$  and thin fibers of  $10 \mu\text{m}$  -  $1000 \mu\text{m}$ . This trend of research progress exists because fog droplets at

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\* The contents in this chapter have been published in *Separation and Purification Technology* 354: 129137.

a low velocity are more likely to pass around thick fibers instead of being captured, thus requiring the reduction of fiber diameter to better capture the droplets [10, 12].

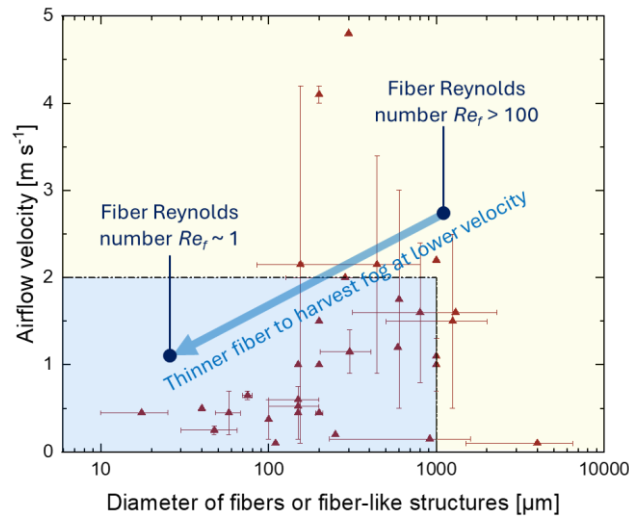


Figure 3.1. Literature on fog harvesting between 2010 - 2024 according to the diameter of the fibers and the airflow velocity. Data points are obtained from Refs. [7, 18, 20, 24, 29, 30, 33, 56, 59, 62, 66, 67, 71, 78, 80, 157-169].

However, the existing theories and design rubrics for fog harvesting may not work for thin-fiber grids at low airflow velocities. First, the Reynolds number of airflow past a fiber reduces from 100 to 1 when approaching a low velocity of  $1 \text{ m s}^{-1}$  and a small fiber diameter of  $10 \text{ } \mu\text{m}$ . The decreasing small Reynolds number indicates that viscous effects start to dominate the flow field around fibers. The viscous effects may further affect the flow boundary layers, separation, recirculation, and pressure loss over the grid, which all influence the water collection efficiency. However, the viscous effects are not addressed in existing theories and design rubrics. In addition, the widely accepted rubrics for avoiding water clogging have been proven limited by recent studies. For example, Park et al. reported that meshes clogged by water bridge have higher collection efficiency compared to the unclogged meshes [62]. Therefore, investigating the water collection efficiency of thin-fiber collectors, especially in the presence of water clogging, is necessary to extend the existing theories and shape new rubrics for collector design.

Numerical modeling is a time-efficient and practically viable approach to study fog harvesting on thin-fiber collectors with the presence of clogging waterdrops, considering the challenges associated with resource-intensive experimental approaches. Experimental investigation proves difficult to probe the flow field around the collector and the fibers [13, 170], where the length scale differs by three orders of magnitude. In addition, the size of the clogging waterdrop dynamically changes with time during the experiment, which raises

difficulty in assessing the influence of water clogging on water collection efficiency. In contrast, numerical methods are proven effective in modeling the flow field around the collector [13] and fibers [160, 171], and controlling the sizes of waterdrops by adjusting modeling parameters [78].

Previous numerical studies have investigated fog collection at two extreme length scales separately. For example, Carvajal et al. studied the overall flow field at the collector scale by modeling the collector as a porous medium and neglecting the actual structures at the fiber scale [13]. The model enables the investigation of the aerodynamic efficiency of fog collectors at different airflow conditions. In addition, Zefrehei et al. modeled the actual structure of the fiber grid to study how grid geometry affected the deposition of fog droplets without considering the overall flow field at the collector scale [171]. Therefore, current numerical methods are hampered by the difficulty of coupling the two scales, resulting in limited study of overall collection efficiency.

The objective of this chapter is to extend the existing theories and shape new design rubrics for thin-fiber fog collectors at a low airflow velocity. A numerical model which innovatively couples the two length scales is developed to investigate the effects of grid geometries and water clogging on water collection efficiency. The model is validated by experimental data and used to study the water collection efficiency of thin-fiber grids with various fiber diameters (10  $\mu\text{m}$  - 1000  $\mu\text{m}$ ) and spacings (0.02 mm - 64 mm) for different clogging scenarios at an airflow velocity of 1  $\text{m s}^{-1}$ . As a result, two important effects that have been previously neglected are identified and discussed, thus extending the existing theory. The findings also suggest new rubrics of geometric design and drainage capacity for fog collectors.

## 3.2 Numerical modeling

### 3.2.1 Model development

The overall water collection efficiency  $E$  is modeled on two length scales based on the theoretical frameworks reviewed in Section 2.2. Assuming that the draining efficiency is approximately 1 due to the negligible re-entrainment at a low airflow velocity of 1  $\text{m s}^{-1}$ , the overall water collection efficiency is expressed as follows.

$$E = \frac{u_p}{u_0} SC \eta_{de} \quad (40)$$

The penetrating and circumventing of airflow takes place in the scale of the collector, whereas the droplet deposition takes place in the scale of fiber and water clogging. Then, Eq.(40) is reorganized into Eqs.(41)-(43) to define the contributions of the two length scales to the overall collection efficiency.

$$E = \eta_a \eta_b \quad (41)$$

where 
$$\eta_a = \frac{u_p}{u_0} \quad (42)$$

$$\eta_b = SC \eta_{cap} \quad (43)$$

Physically,  $\eta_a$  represents the ratio of fog-laden airflow that penetrates the collector to the unperturbed airflow that is directed towards the area of the collector, which takes place at the scale of collector. On the other hand,  $\eta_b$  represents the ratio of captured droplets to the overall challenge droplets, which takes place at the scale of fibers and clogging waterdrops. This new form of collection efficiency allows modeling water collection efficiency at the two length scales separately.

Figure 3.2a illustrates the physical models for the two scales to study the water collection efficiencies. The overall flow field and droplet trajectory around the collector are simulated in a full-size model. In the model, an even airflow with velocity,  $u_0$ , carries fog droplets of diameter,  $d_{fog}$ , to enter a surrounding domain. A collector domain with a diameter of  $L_d$  and a thickness of  $L_t$  is immersed in the airflow to interact with the incoming airflow and droplets. In addition, the flow field and droplet trajectory inside the collector domain are simulated in a close-up model. The fog-laden airflow passes through the grid with a velocity,  $u_p$ , and the flow and challenge droplets interact with a fiber grid modeled by a solid obstacle with the geometrical parameters of fiber diameter,  $d_{fiber}$ , and spacing,  $l_{sp}$ . If the grid is clogged by waterdrops, a spherical obstacle with a radius of  $r_c$  is added at the fiber intersection because the drops usually grow at fiber intersections that provide larger surface areas [56-58]. The close-up model focuses on a steady-state collection without considering the dynamic shedding of waterdrops.

Notably, the close-up model focuses on a steady-state collection without considering the dynamic process of waterdrop shedding and the coalescence between large and small waterdrops. This is because the shedding and coalescence of waterdrops can be represented by the variation of waterdrop radius, which is considered in the parametric study of  $R_c$  in Section

3.3.4. In addition, the wetting and dewetting process of the waterdrops, including water spreading, triple contact line pinning, etc., are not modeled, because 1) the wettability of fiber grids is beyond the scope of this study, and 2) modeling the wetting and dewetting process requires expensive calculations associated with the numerical methods, such as the VOF method [172, 173] and phase field method [174, 175]. Conversely, the present model accurately predicts efficiency without expensive calculations, as validated in Section 3.2.6.

The geometrical parameters of interest are presented in the following dimensionless forms to better interpret results. First, this work uses  $\chi = d_{\text{fiber}}/d_{\text{fog}}$  as the dimensionless fiber diameter, representing the relative scale of fiber to fog droplets. Second,  $\delta = l_{\text{sp}}/d_{\text{fiber}}$  is used as the dimensionless fiber spacing, representing the opening of the grid. Third, the clogging size is described by  $\phi = r_c/l_{\text{sp}}$  to characterize the obstruction of grid openings by water clogging. These dimensionless parameters also allow the comparison to the results with those of Park et al. [12] for a better understanding of geometrical and clogging effects (see Section 3.3.1).

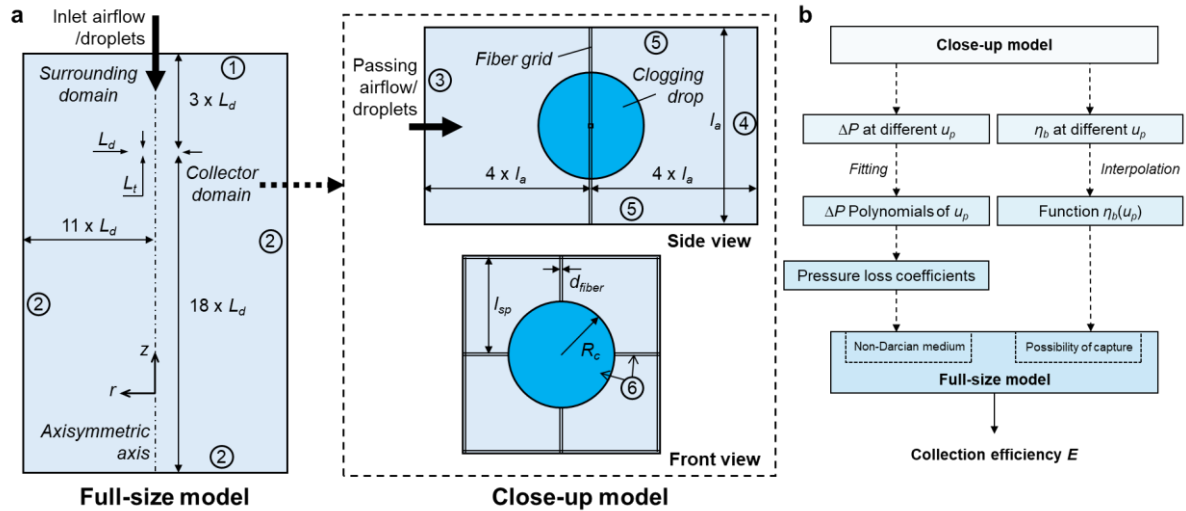


Figure 3.2. Numerical modeling of fog harvesting by fiber grids. (a) Schematic of fog harvesting modeling at two length scales – full-size model and close-up model. (b) Schematic of the coupling method for the full-size and close-up models.

The full-size model is developed further with the following simplifications. First, the surrounding domain is simulated as an axisymmetric turbulent wind tunnel, which controls the airflow conditions and simplifies the model to a two-dimensional one. The typical Reynolds number of airflow using  $L_d$  as the characteristic length is larger than  $10^5$ , which indicates a turbulent flow around the collector. Second, the boundary distances to the collector center, as shown in Figure 3.2a, are chosen to prevent the tunnel boundaries from artificially affecting the flow field around the collector [13]. Third, the collector domain is modeled as a non-

Darcian porous medium generating a resistance consisting of both viscous and dynamic losses, which is based on the results of a flat plate with arbitrary porosity from Steiros et al. [39].

The close-up model involves the following simplifications. First, the model assumes a laminar flow within the domain, because the airflow penetrating the grid has a small Reynolds number  $Re_f$  in the range of 0.1-70 using fiber diameter as the characteristic length. Second, the clogging waterdrop is approximated as a rigid sphere with the non-slip condition applied on its surface. The approximation from a liquid drop to a solid sphere ignores the boundary slip on water-vapor interfaces as well as the deformation of the waterdrop. The rationality of such approximation has been successfully validated in investigating drop-flow interactions [176, 177] and particle capture on waterdrops [178]. Third, only the velocity component that is normal to fiber grid is considered. The contributions of the other two components to pressure loss and droplet capture are ignored, which alleviates the requirement for designing numerous parametric studies for airflow direction. These simplifications are validated to accurately predict the collection efficiency.

In both models, the flight and capture of the fog droplets are simulated as the motion and collisions of discrete particles. The motion of droplets suspended in the airflow is driven by the drag force of the air. As the trajectory of a moving droplet propagates towards the domain boundary, the droplet collides with the boundary and is considered captured. During the motion, water evaporation and gravity are neglected. The two models use the same droplet diameter without considering the size distribution [13].

Figure 3.2b illustrates the method to couple the two models. The close-up model generates results in the pressure loss of grid  $\Delta p$  and the ratio of captured droplets  $\eta_b$  at different  $u_p$ . Following the non-Darcian flow model, the pressure loss  $\Delta p$  as a function of  $u_p$  is then fitted to a second-order polynomial to extract the first-order and second-order coefficients as the viscous and dynamic loss coefficients [13]. The two coefficients are input into the collector domain in the full-size model to solve flow field. In addition, the ratio  $\eta_b$  is interpolated as a curve related to the penetrating velocity [6, 10]. The curve function is used in the full-size model to determine the possibility of capturing the challenge droplets that enter the collector domain to solve droplet trajectory. In this way, two models are uni-directionally coupled, and the full-size model can be solved for the overall collection efficiency  $E$  using inputs from the close-up model. It should be noted that the two models are not bi-directionally coupled, because the velocity  $u_0$  in the full-size model and  $u_p$  in the close-up model are independent of each other.

### 3.2.2 Governing equations

#### Flow field

This study uses incompressible Navier-Stokes equations to solve the velocity and pressure profiles in full-size and close-up models, as shown in Eqs. (44)-(45)

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u} \cdot \nabla \mathbf{u}) = -\nabla P + \nabla \cdot \boldsymbol{\tau} \quad (44)$$

$$\rho \nabla \cdot \mathbf{u} = 0 \quad (45)$$

where  $\rho$ ,  $\mathbf{u}$ , and  $p$  are the density, velocity, and pressure of the air;  $\boldsymbol{\tau}$  is the viscous stress tensor, which is calculated depending on whether the flow is laminar or turbulent. For a laminar flow,

$$\boldsymbol{\tau} = \mu(\nabla \mathbf{u} + (\nabla \mathbf{u})^T) \quad (46)$$

where  $\mu$  is the air dynamic viscosity. For a turbulent flow,

$$\boldsymbol{\tau} = (\mu + \mu_T)(\nabla \mathbf{u} + (\nabla \mathbf{u})^T) \quad (47)$$

where  $\mu_T$  is the turbulent viscosity. This study uses the Realizable k- $\varepsilon$  turbulence model to solve the turbulent viscosity  $\mu_T$  because the model better predicts flows with strong adverse pressure gradients and recirculation, which commonly occurs around fog collectors [13]. Other methods such as k- $\omega$  SST model have been proven effective for near-wall flows. However, the full-size model ignores “wall” property of the collector to simulate it as a porous media, which alleviates the treatment for near-wall flows. The mathematical form of Realizable k- $\varepsilon$  model is expressed as

$$\rho(\mathbf{u} \cdot \nabla)k = \nabla \cdot \left[ \left( \mu + \frac{\mu_T}{\sigma_k} \right) \nabla k \right] + P_k - \rho\varepsilon \quad (48)$$

$$\rho(\mathbf{u} \cdot \nabla)\varepsilon = \nabla \cdot \left[ \left( \mu + \frac{\mu_T}{\sigma_k} \right) \nabla \varepsilon \right] + C_{\varepsilon 1} \rho S \varepsilon - C_{\varepsilon 2} \frac{\rho \varepsilon^2}{k + \sqrt{\mu \varepsilon / \rho}} \quad (49)$$

where  $k$  is turbulent kinetic energy, and  $\varepsilon$  is turbulent dissipation rate. Additionally,

$$C_{\varepsilon 1} = \max \left\{ 0.43, \frac{\eta}{5 + \eta} \right\} \quad (50)$$

$$\eta = \frac{Sk}{\varepsilon} \quad (51)$$

$$S = \sqrt{2\mathbf{S} : \mathbf{S}} \quad (52)$$

$$\mathbf{S} = \frac{1}{2}(\nabla \mathbf{u} + (\nabla \mathbf{u})^T) \quad (53)$$

The turbulent viscosity is then calculated as

$$\mu_T = \rho C_\mu \frac{k}{\varepsilon} \quad (54)$$

where

$$C_\mu = \frac{1}{A_0 + A_s U^* \frac{k}{\varepsilon}} \quad (55)$$

$$A_s = \sqrt{6} \cos\left(\frac{1}{3} \arccos(\sqrt{6}W)\right) \quad (56)$$

$$W = \frac{2\sqrt{2}\mathbf{S} : (\mathbf{S} \cdot \mathbf{S})}{|\mathbf{S}|^3} \quad (57)$$

$$U^* = \sqrt{\mathbf{S} : \mathbf{S} + \mathbf{\Omega} : \mathbf{\Omega}} \quad (58)$$

$$\mathbf{\Omega} = \frac{1}{2}(\nabla \mathbf{u} - (\nabla \mathbf{u})^T) \quad (59)$$

$$P_k = \mu_T [\nabla \mathbf{u} : (\nabla \mathbf{u} + (\nabla \mathbf{u})^T)] \quad (60)$$

The parameters used in Eqs. (48)-(60) are  $A_0 = 4.04$ ,  $C_{2\varepsilon} = 1.9$ ,  $\sigma_k = 1.0$ , and  $\sigma_\varepsilon = 1.2$  [13].

In addition, the resistance of the collector in the full-size model is solved using a non-Darcian flow model for porous media. The non-Darcian flow model takes the form of Eq. (61).

$$-\nabla p = C_1 \mathbf{u} + C_2 |\mathbf{u}| \mathbf{u} \quad (61)$$

where  $C_1$  is the viscous loss coefficient, and  $C_2$  is the inertial loss coefficient. The pressure gradient  $\nabla p$  can be expressed as  $\nabla p = \Delta p / L_t$ , where  $L_t$  is the known thickness of the collector. To obtain the unknown coefficients  $C_1$  and  $C_2$ , the pressure loss  $\Delta P$  over fiber grids calculated by the close-up model is correlated with penetrating velocity  $u_p$ . Figure 3.3 gives an example of correlating the pressure loss of three grids with  $d_{\text{fiber}} = 100 \mu\text{m}$  and  $\delta = 4, 8$  and  $16$ . The simulation results of the close-up model are plotted as dots, exhibiting the mathematical

property of second order polynomials, which is consistent with the non-Darcian flow model. The results are then fitted onto second order polynomial curves with a R-square of 1, and the respective first order and second order coefficients are extracted from the fitting curve formula as  $A_1$  and  $A_2$ .  $C_1$  and  $C_2$  are then obtained as  $A_1 L_t$  and  $A_2 L_t$ , respectively.

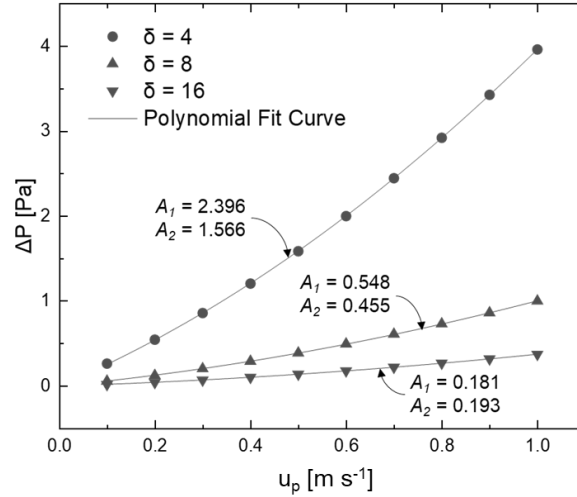


Figure 3.3. Correlating pressure loss with penetrating air velocity and the second-order polynomial fitting curve.

### *Droplet trajectory*

The motion of fog droplets released into the model domain follows Newton's second law:

$$\frac{d(m_{fog} \mathbf{v})}{dt} = F_d \quad (62)$$

where  $m_{fog}$  and  $\mathbf{v}$  are the mass and velocity of the droplet, respectively. The drag force  $F_d$  is due to the velocity difference between the air and the droplets, which follows Stokes' law in Eq. (63).

$$F_d = \frac{m_p}{\tau} (\mathbf{u} - \mathbf{v}) \quad (63)$$

$$\tau = \frac{\rho_w d_{fog}^2}{18\mu} \quad (64)$$

where  $\rho_w$  and  $d_{fog}$  are the density and diameter of the fog droplet, respectively. The air velocity vector  $\mathbf{u}$  is obtained from the air velocity profile obtained from the preceding continuous phase Eulerian fluid dynamics analysis.

The trajectory of the droplet evolves with time, which is calculated by applying a small displacement of  $\mathbf{v}dt$  for each time step  $dt$ . When the propagating trajectory in the domain

intercepts with any wall boundaries, the droplet is captured and its velocity is instantly reduced to zero to prevent any further movement.

### 3.2.3 Boundary and initial conditions

The boundary conditions for the system of differential equations are set up according to the boundaries detailed in Figure 3.2a. The problem of fluid dynamics is solved at a steady state using the following boundary conditions.

$$\text{Velocity inlet ①} \quad u_{\perp} = u_0, u_{\parallel} = 0 \quad (65)$$

$$\text{Pressure outlet ②} \quad P = 1 \text{ atm} \quad (66)$$

$$\text{Velocity inlet ③} \quad u_{\perp} = u_P, u_{\parallel} = 0 \quad (67)$$

$$\text{Pressure outlet ④} \quad P = 1 \text{ atm} \quad (68)$$

$$\text{Symmetry ⑤} \quad u_{\perp} = 0 \quad (69)$$

$$\text{Non-slip wall ⑥} \quad \mathbf{u} = 0 \quad (70)$$

The subscripts “ $\perp$ ” and “ $\parallel$ ” denote the vector components normal and parallel to the boundary, respectively.

Furthermore, the problem of droplet motion is solved in a Lagrangian formulation as presented earlier, using the following initial and boundary conditions.

$$\text{Release ①, } t = 0 \quad \mathbf{v} = \mathbf{u} \quad (71)$$

$$\text{Walls ⑥} \quad \mathbf{v} = 0 \quad (72)$$

The number of released droplets is determined by varying the number of droplets until the ratio of captured droplets no longer changes, thus ensuring a minimum required number. As a result, 500 droplets provide sufficient samples to represent the fog droplets going through the collection process, allowing a rather accurate prediction of motion and capture of droplets.

### 3.2.4 Numerical solutions of the equations

Both the full-size and close-up models are solved by the finite element method (FEM) using the COMSOL Multiphysics 5.6 software, which is widely used for studies on fog harvesting

modeling [33, 78, 179, 180]. Specifically, the fluid mechanics problem is solved using a computational fluid dynamic interface; the droplet trajectory problem is solved using a particle tracing interface.

Table 3.1 and Table 3.2 show the model parameters and the fluid properties used in this study. First, the fiber diameter ranges from  $d_{\text{fiber}} = 10 \mu\text{m} - 1000 \mu\text{m}$  based on the small fiber diameters that has been used in existing studies. In addition, the fiber spacing is selected by putting dimensionless parameter  $\delta$  to spread in the range of 2-64, yielding a reasonable shade coefficient of  $SC = 0.03-0.75$ . Second, the parameter of clogging size  $\varphi = 0$  to 1 is used for the isolated clogging drop which grows from absence to fully block an opening unit of the grid, indicating the radius  $r_c$  is less than the fiber spacing  $l_{\text{sp}}$ . In practice, the drops can grow to a larger size, which is discussed in Section 3.3.5 by introducing connected clogging with  $\varphi > 1$ .

Table 3.1. Parameters used in the present numerical calculations

| Parameter          | unit              | full-size model | close-up model                                     |
|--------------------|-------------------|-----------------|----------------------------------------------------|
| $\delta$           |                   |                 | 2-64                                               |
| $d_{\text{fiber}}$ | $\mu\text{m}$     |                 | 10-1000                                            |
| $\varphi$          |                   |                 | 0-1 (isolated clogging)<br>>1 (connected clogging) |
| $u_0$              | $\text{m s}^{-1}$ | 1               |                                                    |
| $u_p$              | $\text{m s}^{-1}$ |                 | 0-1                                                |
| $L_d$              | m                 | 0.2             |                                                    |
| $L_t$              | mm                | 0.5             |                                                    |
| $d_{\text{fog}}$   | $\mu\text{m}$     | 8, 16, 32       | 8, 16, 32                                          |

Table 3.2. Fluid properties used in the present numerical calculations

| Fluid properties | unit               | water | air                   |
|------------------|--------------------|-------|-----------------------|
| Density $\rho$   | $\text{kg m}^{-3}$ | 1000  | 1.293                 |
| Viscosity $\mu$  | $\text{Pa s}$      |       | $1.81 \times 10^{-5}$ |

Third, the present study is conducted at a fixed inlet velocity of  $u_0 = 1 \text{ m s}^{-1}$  and a fixed collector size of  $L_d = 0.2 \text{ m}$  and  $L_t = 0.5 \text{ mm}$ . The velocity is selected as  $1 \text{ m s}^{-1}$  because thin-fiber collectors are developed for applications at low wind speeds close to  $1 \text{ m s}^{-1}$  [20, 26, 56,

59, 78, 80, 163, 164]. When  $u_0 \gg 1 \text{ m s}^{-1}$ , water collection efficiency is monotonically incremental to the shades of the mesh instead of related to the specific structure of the fibers, which has already been verified [62]. In addition, the variation of  $L_d$  in the range of 0.1-2 m and  $L_t$  in the range of 0.1-1 mm imposes a negligible effect on the collection efficiency, as shown in Figure 3.4. Therefore, choosing these parameters values suffices for the purpose of this study.

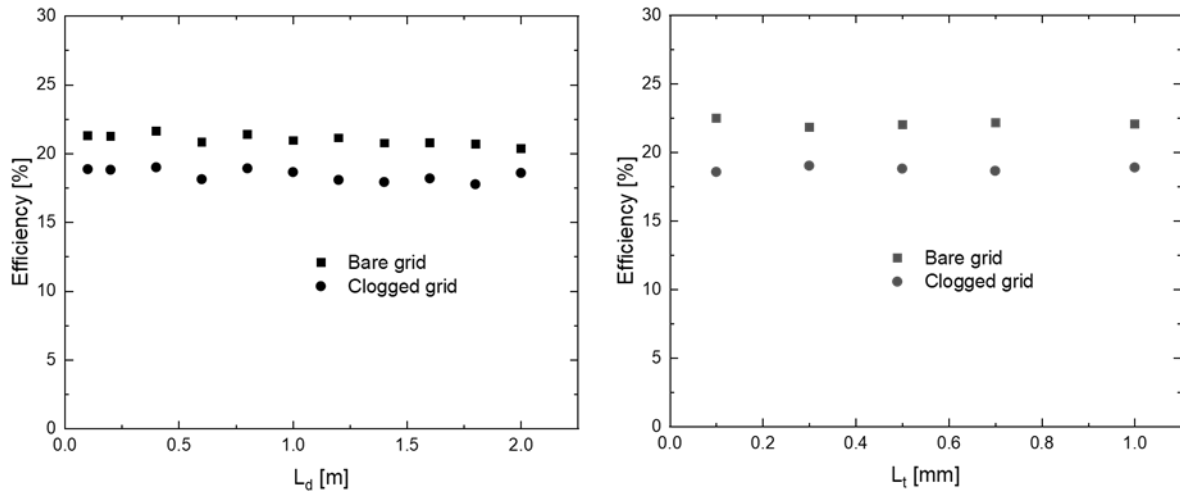


Figure 3.4. Influence of collector size on collection efficiency. Results are for (a)  $L_d$  and (b)  $L_t$  of collector with  $d_{\text{fiber}} = 100 \mu\text{m}$  and  $\delta = 5$  for  $16 \mu\text{m}$  fog droplets. The clogging size for the clogged grid is  $\varphi = 0.56$ .

Last, the fog droplet size in the model is selected as  $d_{\text{fog}} = 8 \mu\text{m}$ ,  $16 \mu\text{m}$  and  $32 \mu\text{m}$ . In practice, the diameter of fog droplets usually spans over a wide range of  $2\text{-}50 \mu\text{m}$  [17] and is difficult to control. However, previous experimental studies use smaller average droplet diameters of  $10\text{-}20 \mu\text{m}$  [12, 20, 80, 181] to ensure that the results are not biased by the large droplets that are easier to capture. This study uses fog droplets of  $8, 16$ , and  $32 \mu\text{m}$  to better evaluate the influence of  $d_{\text{fog}}$  on collection efficiency.

### 3.2.5 Grid independence

Figure 3.5a and b show the meshed domains of full-size and close-up models. Structured rectangle elements are adopted to mesh the region around the collector in the full-size model and the rest of the domain with unstructured triangle elements. This meshing strategy ensures a balance of meshing quality and computational cost [13]. In addition, the close-up model is meshed using unstructured tetrahedron elements due to the complex geometry of clogging and fibers [171]. Boundary layer meshes are refined using the automatic profiling function of COMSOL Multiphysics. All models studied use the same node density to ensure a similar simulation quality.

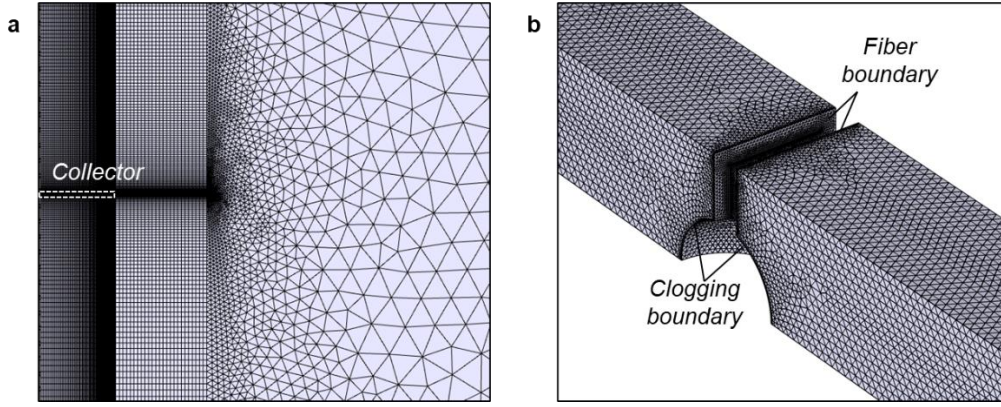


Figure 3.5. Images of meshed domain of developed models. (a) Full-size model. (b) Close-up model.

Grid independence tests are performed for each of the two models. For the full-size model, the velocity profile is evaluated along the  $r$  axis across the collector midline. Figure 3.6a shows that three numbers of meshes, 13,000, 40,000, and 85,000, give a similar result of velocity distribution across the domain. However, 40,000 and 85,000 meshes show smaller discrepancies at  $r/L_d = 1$  and  $r/L_d = 1.5$  compared to 13,000 meshes (see Figure 3.6a insets). Therefore, the full-size model uses 40,000 meshes. For the close-up model, the pressure loss over the grid is evaluated with 120,000, 240,000, 700,000, and 1,600,000 meshes. Figure 3.6b shows that using 700,000 meshes leads to a satisfactory result with a 0.5% discrepancy compared to 1,600,000 meshes. Therefore, 700,000 meshes are chosen to profile the close-up model domain.

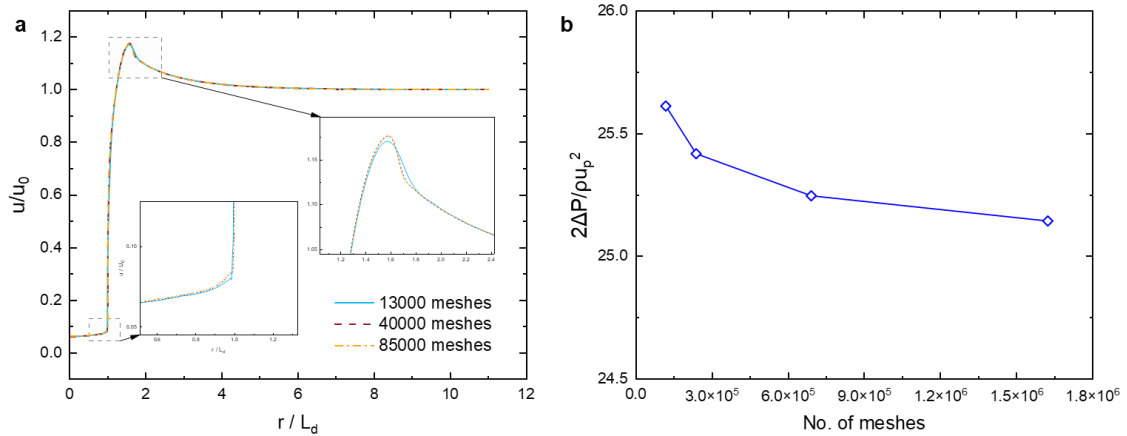


Figure 3.6. Plots of grid independence test results. (a) Full-size model by comparing the velocity profiles for 13,000, 40,000, and 85,000 meshes. (b) Close-up model by comparing pressure loss over the collector with different numbers of meshes.

### 3.2.6 Validation

The close-up and full-size models are validated separately by comparing with published experimental results. The model parameters used for validation are extracted from the published results and provided in Appendix A.

The full-size model is validated using the overall collection efficiencies  $E$  from experimental studies. As shown in Figure 3.7a, the present simulation results of the different structures of fog collectors, i.e., Raschel mesh, fog harps, and microfiber grids, are compared to experimental results provided by the existing studies [12, 78, 80]. The efficiency  $E$  calculated by the full-size model shows a similar trend as the experimental one. A paired-data  $t$  test shows a  $p$  value of 0.4 at a significance level of 0.05, indicating the insignificant difference between the simulation and experiments. The discrepancies between the model predictions and experimental data are acceptable considering that a standard method of fog collection experiments is so far unavailable, and reported test conditions such as droplet size, airflow, and collector scale normally vary in previous studies. Overall, the full-size model can predict  $E$  with satisfactory accuracy.

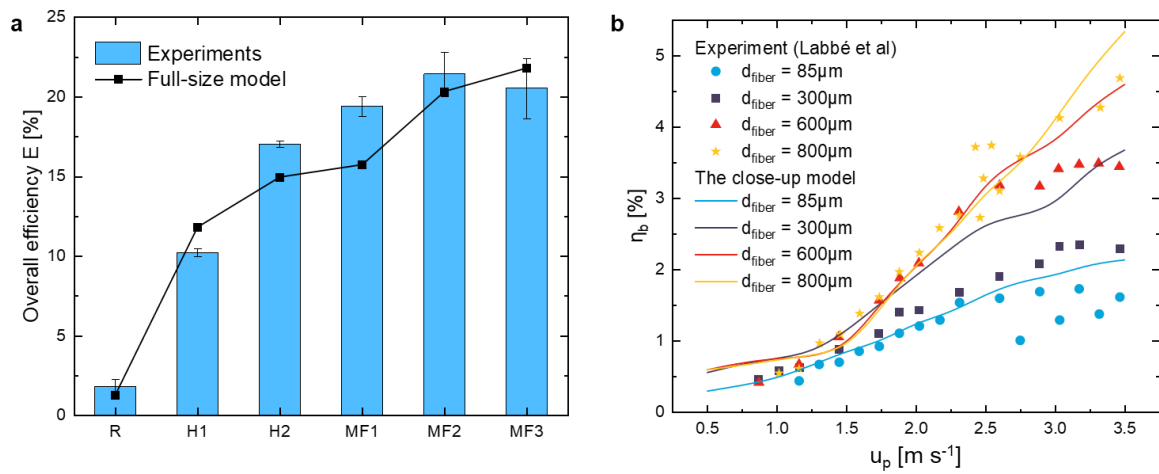


Figure 3.7. Plots of model validation results. (a) Validation of the full-size model by comparing to experimental studies with distinct structures of collectors (symbols R – Raschel mesh [12]; H1, H2 – Fog harp with  $\delta = 4$  and 2 [80]; MF1, MF2, MF3 – Micro-fiber grid with  $\delta = 20, 30$  and 40 obtained from Chapter 4). (b) Validation of the close-up model by comparing with the published experimental data [24] for fibers with attached drops.

The close-up model is validated using the ratio of captured droplets  $\eta_b$  reported by Labbé et al. for fog droplets deposited on wet vertical fibers [24]. The geometries of fibers and drops are modified according to the reported data. Figure 3.7b shows that the simulated ratios of captured droplets,  $\eta_b$ , are consistent with the experimental results for  $u_p$  between 0.5 - 3.5 m s<sup>-1</sup> and  $d_{\text{fiber}}$  from 85 to 800 μm. A paired-data  $t$  test shows a  $p$  value of 0.3 at a significance level

of 0.05, indicating the insignificant difference between the simulation and experiments. It is noted that a larger discrepancy exists when comparing with the experimental results for  $d_{\text{fiber}} = 300 \mu\text{m}$ , this is because of the distribution of fog droplet size as discussed by Labbé [27]. Therefore, the close-up model is considered satisfactory to predict  $\eta_b$  for the given range of fiber diameter and air velocity.

### 3.3 Results and discussion

#### 3.3.1 Flow field and droplet capture

Figure 3.8a illustrates the flow field in the full-size model for four different fiber-grid structures. The magnitudes of gauge pressure and velocity are plotted using dimensionless forms as  $\bar{p} = p/(1/2\rho u_0^2)$  and  $\bar{u} = u/u_0$ , respectively. Here, the grid with  $\delta = 2.8$  and  $\chi = 18$  is used as an example. The fiber grid generates resistance to airflow with a pressure loss coefficient of  $C_P = 133$ . Specifically, the pressure is elevated upstream of the collector to a maximum of 0.87 due to the resistance. The pressure gradient divide airflow into two streams. The stream circumventing the collector has a large velocity of  $\bar{u} = 0.5$ -1.2; whereas the airflow penetrating the collector has a lower velocity of  $\bar{u} = 0.1$ -0.24. The velocity gradient created by circumventing and penetrating airflow generates a shear layer along the edge of the collector, leading to flow separation and recirculation [39]. The flow recirculation then creates negative pressure with a maximum  $\bar{p} = -1.46$  downstream of the collectors.

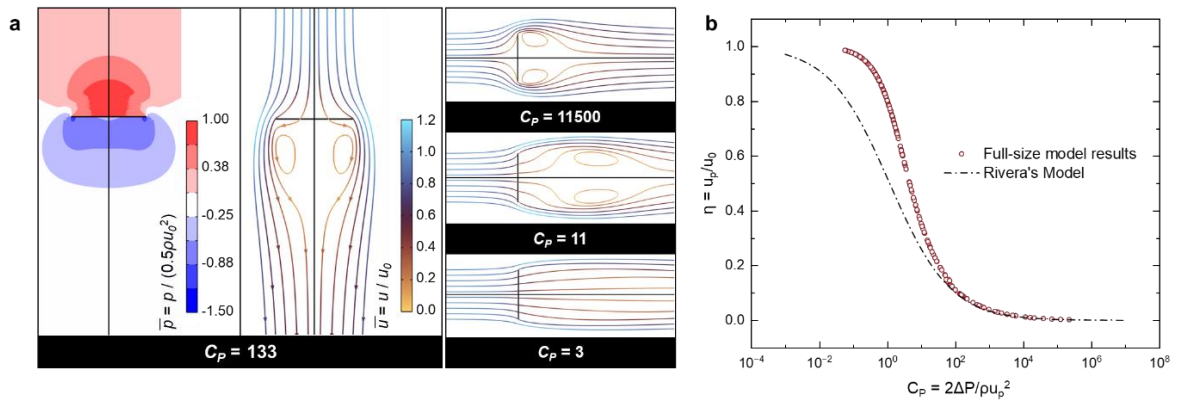


Figure 3.8. Simulation results of the full-size model. (a) Pressure and velocity profile around collector with pressure loss coefficient  $C_P = 133$  in the full-size model, and the variation of velocity profile at  $C_P = 11500$ , 11 and 3. (b) Simulation results for the ratio of penetrating airflow  $\eta_a$  versus  $C_P$ .

In addition, the pressure loss coefficient  $C_P$  determines the fraction of airflow that passes through the collector. Different  $C_P$  of fiber grid (i.e., 11500, 11, and 3) are obtained by altering the fiber diameter and spacing to change the resistance to airflow. As shown in Figure 3.8a, more airflow passes through the collector as  $C_P$  is decreased from 11500 to 3 due to an increase

in the collector opening area or a decrease in the clogging area. Notably, the flow recirculation gradually moves downstream as the  $C_P$  is decreased and eventually disappears when  $C_P$  is reduced to 3. The suppressed recirculation at a small  $C_P$  results from the enhanced penetrating airflow that weakens the shear layer [39]. Using Eq. (42), the ratio of penetrating airflow  $\eta_a$  is calculated as the ratio between the average penetrating velocity  $u_p$  and inlet velocity  $u_0$ . As a result, the ratio of penetrating airflow  $\eta_a$  reduces from 1 to 0 as  $C_P$  increases from  $10^{-1}$  to  $10^6$  (see Figure 3.8b), indicating a transition of the collector permeability to airflow from fully permeable to impermeable. Specifically, all the simulation results with different grid geometries and clogging conditions collapse onto the same curve of  $\eta_a = 1.43(C_P + 1.85)^{-0.56}$  with  $R^2 > 0.99$ , indicating that  $\eta_a$  is only determined by  $C_P$  regardless of the individual viscous and dynamic loss coefficients  $C_1$  and  $C_2$ . Overall, the penetrating airflow ratio  $\eta_a$  increases as the collector pressure loss coefficient  $C_P$  is decreased, suggesting that more airborne fog droplets can interact with the collector, and in turn, being captured.

Furthermore, the present model generally predicts a higher  $\eta_a$  value compared to Rivera's model for  $C_P < 100$ . This is because the potential flow theory used by Rivera [21] is insufficient in predicting the penetrating flow driven by the pressure difference due to recirculation. Carvajal et al. reported the same inconsistency between their numerical models and Rivera's model [13]. Therefore, Rivera's model should be further corrected to include the effects of flow recirculation to better predict penetrating airflow ratio and overall water collection efficiency.

Figure 3.9a shows the simulated trajectory of challenge droplets in the close-up model for a bare grid. The droplets enter the domain at the same velocity with airflow at  $\bar{v} = v/u_p = 1$ . The velocity  $\bar{v}$  of the escaped droplets increases to 1.4 - 1.6 because the passage area is reduced from 100% to 67.5%. Notably, partial droplets that would have been directed toward the fibers are deflected and thus escape due to the viscous drag of the airflow and the growth of the boundary layers around the fibers. Only those with sufficient momentum to overcome the drag can be captured by fibers; the fraction of these captured droplets is described by the normalized  $\eta_b = \eta_b/SC$  according to Eq.(43), where  $SC = (2\delta - 1)/\delta^2$  is for square grids. The normalized  $\eta_b$  denotes the fraction of the droplets impacting the fiber grids with mass center in the fiber projected area.

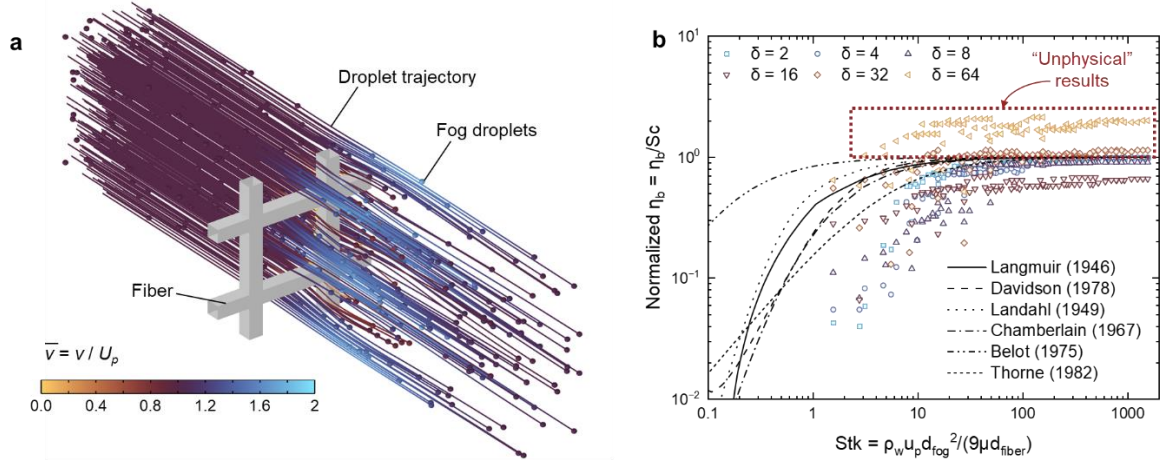


Figure 3.9. Simulation results of the close-up model without clogging waterdrops. (a) Droplet trajectory passing through a bare grid with  $\delta = 5.6$  and  $\chi = 6.3$ . (b) Comparison of the present simulations with existing single-fiber models in terms of normalized ratio of captured droplets.

To compare the results for the bare grids to the existing single-fiber models of droplet deposition, the normalized  $\eta_b$  for bare grids with  $\delta = 2$ -64 and  $\chi = 0.6$ -60 is correlated to the fiber Stokes number  $Stk = \rho_w d_{fog}^2 u_p / (9 \mu d_{fiber})$  (see Figure 3.9b). The correlation reveals that the normalized  $\eta_b$  generally increases with  $Stk$  and remains almost unchanged at  $Stk > 10$ , because the droplets with higher  $Stk$  ballistically impact the fibers by overcoming the air viscous drag [182]. Overall, the ratio of the captured droplets  $\eta_b$  is higher for thinner fibers with larger  $Stk$ .

However, the present simulation results show an additional dependence of the normalized  $\eta_b$  on the fiber spacing  $\delta$ , which differs from the existing single-fiber models. For example, increasing  $\delta$  from 2 to 8 at a fixed  $Stk = 10$  decreases the normalized  $\eta_b$  from 0.58 to 0.2. However, further increasing  $\delta$  to 16 and 32 leads to a higher normalized  $\eta_b$  of 0.36 and 0.75, respectively. The discrepancy is similar to the experimental result of aerosol deposition on wire meshes from Han et al. [183], where the deposition efficiency at a fixed wire Stokes number of  $Stk = 10$  decreases by -60% as the spacing  $\delta$  of mesh increases from  $\delta = 3.0$  to 18.5. This discrepancy for the normalized  $\eta_b$  to the single fiber models might be attributed to the difference between the fiber grid structures and single fibers, although the cause of the spacing-dependent discrepancy requires further investigation. In addition, the present simulation yields “unphysical” results of the normalized  $\eta_b > 1$ . In fact, the normalized  $\eta_b > 1$  is possible when the diameter of fog droplets and fibers are comparable, where the challenge droplets with mass center outside of fiber projected area can still impact the fiber. This impaction process is similar to particle interception in classic filtration theory, where the interception efficiency monotonically increases with the ratio of the particle size to fiber diameter [19, 40]. Therefore, the single fiber models for droplet deposition require corrections for extension to grid structures

or thin fibers with diameters comparable to fog droplets. Such corrections should be studied separately in the future.

Notably, the existence of waterdrop clogging affects how grids interact with challenge droplets. As shown in Figure 3.10a, a clogging waterdrop is attached to the fiber intersection of the same grid with  $\delta = 5.6$  and  $\chi = 6.3$ . The escaping droplets show a high velocity of  $\bar{v} = 1.8\text{-}2.0$  when passing through the grid opening because the passage area is reduced to 51.9%. In addition, the clogging drop deflects the trajectory of the challenge droplets away by distorting the airflow, which is caused by introducing a larger obstacle with a drop radius of  $r_c$ . As a result, the clogging Stokes number,  $Stk_c = \rho_w d_{\text{fog}}^2 u_p / (18\mu r_c)$ , is adopted to characterize the droplet capture [24, 78]. As shown in Figure 3.10b, the normalized  $\eta_b$  generally correlates with  $Stk_c$ , indicating that the droplet capture mainly depends on the Stokes number of the clogging. The correlation can be fitted against  $\eta_b/SC = (1 + 0.75Stk_c^{-0.75})^{-5}$  with adjusted  $R^2 \approx 1$  regardless of fiber diameter or spacing, indicating that the  $Stk_c$  of clogging dominates the droplet capture. Therefore, the size of waterdrop clogging is important to the overall collection efficiency.

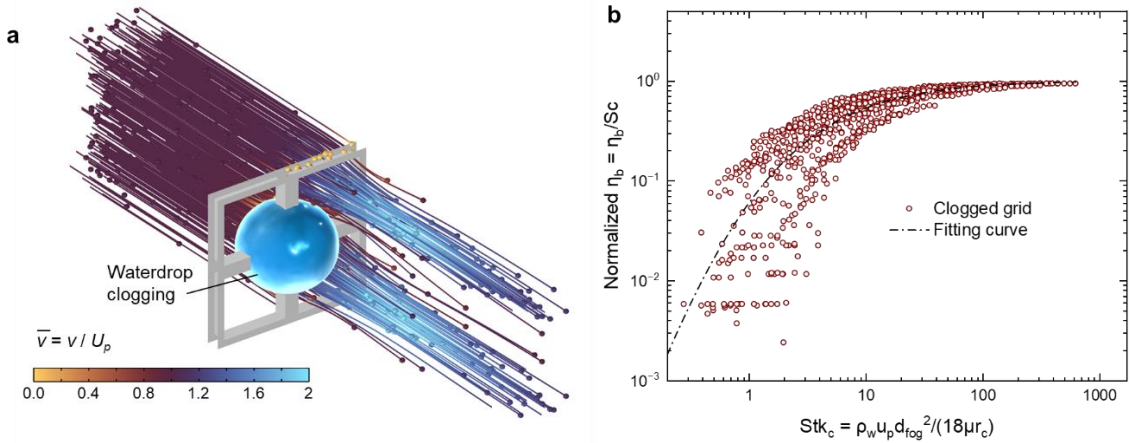


Figure 3.10. Simulation results of the close-up model with clogging waterdrops. (a) Droplet trajectory passing through a clogged grid. (b) The present simulation for the normalized ratio of captured droplets  $\eta_b/SC$  versus clogging Stokes number  $Stk_c$ .

On the other hand, Eq. (43) indicates the unnormalized  $\eta_b$  also increases with the projected area fraction  $SC$ . In contrast to  $Stk$  and  $Stk_c$ ,  $SC$  monotonically increases with fiber diameter and clogging size, suggesting a competing effect between the projected area and the Stokes number. Therefore, a trade-off between the projected area fraction  $SC$  and the clogging Stokes number  $Stk_c$  determines the ratio of the captured droplets  $\eta_b$ .

### 3.3.2 Overall water collection efficiency

Figure 3.11a shows contour plots for the overall water collection efficiency  $E$  for the bare grids  $\delta = 2-64$  and  $\chi = 0.6-60$  at a droplet diameter of  $d_{\text{fog}} = 16 \mu\text{m}$ . The efficiency  $E$  varies from 4 to 24% across different fiber-grid geometries. Specifically, it increases and then decreases as  $\delta$  and  $\chi$  are increased and reaches a peak value of 24% at  $\delta = 4$  and  $\chi = 16$ . The peak efficiency corresponds to the dimensional fiber diameter of  $260 \mu\text{m}$  and fiber spacing of  $1 \text{ mm}$ , leading to  $SC = 0.44$ . Furthermore, the results at fog diameter of  $8 \mu\text{m}$  and  $32 \mu\text{m}$  (see Figure 3.11b and c) lead to a higher collection efficiency at  $\delta = 4-8$  and  $\chi = 8-16$ . Previous experiments proved that collectors with similar diameter and  $SC$  can harvest fog with an optimal overall collection efficiency of 10% - 17% [12, 20, 80]. These values may deviate from the simulation (12% - 28%) because of the different testing conditions such as droplet diameter and airflow velocity. These collectors require surface treatment or a harp-type structure for rapid removal of clogging drops so that the actual surface of the collector is close to a bare grid.

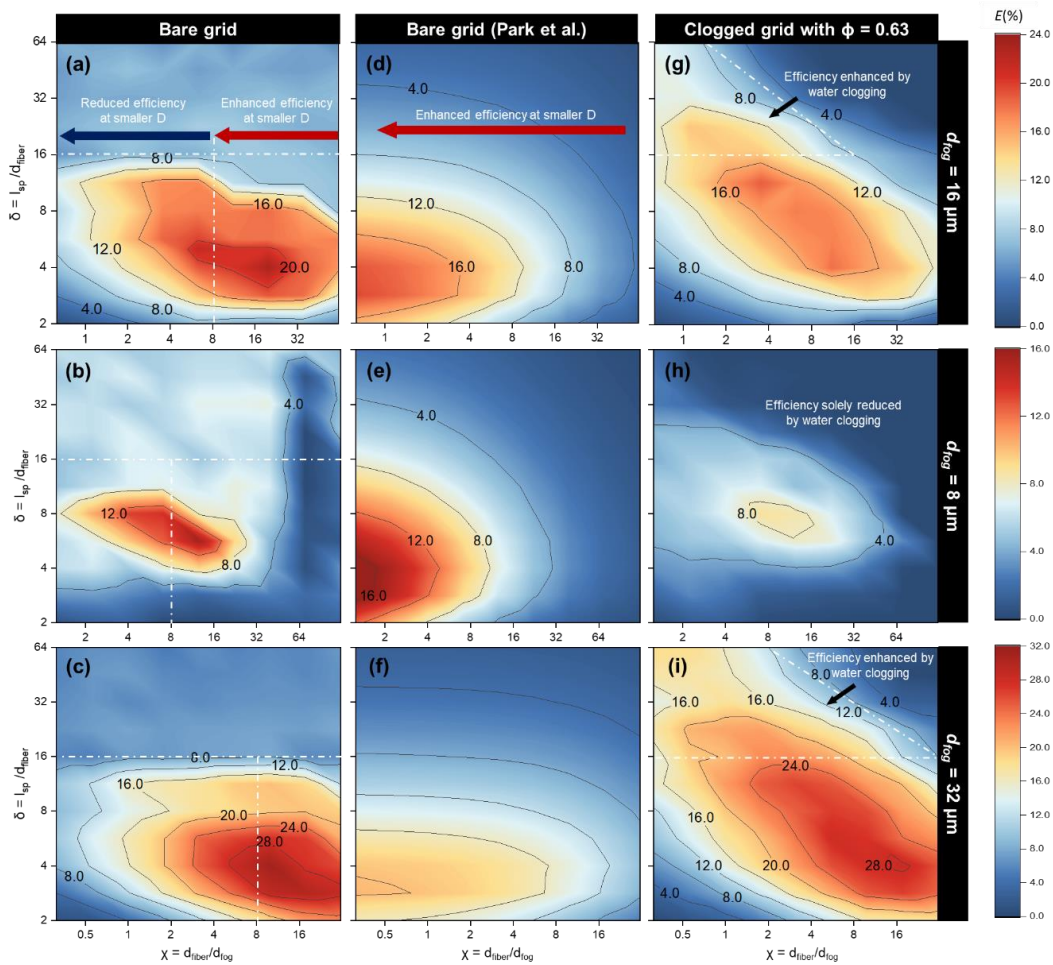


Figure 3.11. Contour plots of the overall water collection efficiency for different grid structures and clogging conditions. (a-c) The present simulation results of the overall efficiency for bare grids without water clogging at  $d_{\text{fog}} = 16 \mu\text{m}$  (a),  $8 \mu\text{m}$  (b), and  $32 \mu\text{m}$  (c). (d-f) Overall efficiency for bare grids at  $d_{\text{fog}} = 16 \mu\text{m}$  (d),  $8 \mu\text{m}$  (e), and

32  $\mu\text{m}$  (f) calculated using the theoretical model proposed by Park et al. [12]. (g-i) The present simulation results of the overall efficiency for clogged grids with  $\phi = 0.63$  at  $d_{\text{fog}} = 16 \mu\text{m}$  (g),  $8 \mu\text{m}$  (h), and  $32 \mu\text{m}$  (i).

The present simulation results are compared to the theoretical model results for bare grids from Park et al. [12] (see Figure 3.11d-f) using the same airflow velocity and fog droplet diameter. The simulation predicts a higher efficiency at  $\chi > 8$  than the theoretical model does, because the theoretical model underestimates the penetrating ratio  $\eta_a$ , as discussed in Section 3.3.1. However, an opposite trend exists in the region of  $\delta < 16$  and  $\chi < 8$  for all  $d_{\text{fog}}$  values ( $8 \mu\text{m}$ ,  $16 \mu\text{m}$ , and  $32 \mu\text{m}$ ). Specifically, the theoretical model predicts that  $E$  monotonically increases with the decreasing  $\chi$ , because a smaller  $\chi$  increases the fiber Stokes number  $Stk$ , leading to an increased  $\eta_b$ . In contrast, the efficiency  $E$  in the present study decreases with decreasing values of  $\chi$  and reaches the lowest efficiency  $E$  of 8-10% at  $\chi = 0.6$ . Therefore, an unidentified effect exists to compete with increased Stokes number, which is examined further in Section 3.3.3.

In addition, the clogged grids with  $\delta > 16$  and  $\chi < 16$  show a higher efficiency for larger fog droplets, i.e.,  $d_{\text{fog}} = 16 \mu\text{m}$  and  $32 \mu\text{m}$ , than the unclogged bare grid. As shown in Figure 3.11g-i, the grid clogged with drops size of  $\phi = r_c/l_{\text{sp}} = 0.63$  shows a different efficiency contour compared to the bare grids. Generally, the efficiency  $E$  is reduced in most of the contour areas when the grid is clogged by waterdrops. However, the region of higher efficiency ( $E > 12\%$ ) for  $d_{\text{fog}} = 16 \mu\text{m}$  and  $32 \mu\text{m}$  shifts towards the upper left corner, which represents sparse thin-fiber grids. The efficiency elevation due to clogging is also observed for other clogging size of  $0 < \phi < 1$ ; therefore, the clogging is considered “positive” to collection efficiency. The positive clogging in this work contradicts the existing design rubrics which deem clogging negative to collection efficiency and is examined further in Section 3.3.4.

### 3.3.3 Wall effect of dense thin-fiber grid

The wall effect due to thick boundary layers explains the reduced efficiency of dense thin fiber grids of  $\delta < 16$  and  $\chi < 8$  as  $\chi$  is decreased. For thin fibers with  $\chi < 8$  in an airflow of  $u_p < 1 \text{ m s}^{-1}$ , the Reynolds number  $Re_f$  ranges from 0.1 to 10, indicating the flow regime transits to creeping flow ( $Re_f < 1$ ) dominated by viscous effect. In creeping flows, the thickness of the flow boundary layers  $y_b$  around fibers can extend several times the fiber diameter  $d_{\text{fiber}}$  (see Figure 3.12a), which is known as the wall effect and estimated using Eq. (73). [77]

$$\frac{y_b}{d_{\text{fiber}}} = \frac{20}{Re_f} \quad (73)$$

For thin fiber arrays in a grid, the thick boundary layer of individual fibers can interact with each other (see Figure 3.12a) when the fibers spacing  $l_{sp}$  is less than  $y_b$ , as estimated by Eq. (74).

$$\delta = \frac{l_{sp}}{d_{fiber}} < \frac{20}{Re_f} \quad (74)$$

Using  $Re_f = 1$  for creeping flow, the wall effect takes place when  $\delta < 20$ , leading to interacting boundary layers that elevate airflow drag and pressure loss [77]. Therefore, the grid of  $\delta < 16$  and  $\chi < 8$  is subjected to the wall effect, which diverts the airflow to circumvent the collector and reduce  $\eta_a$ .

Our simulation verifies the wall effect of dense thin-fiber grids, which is ignored by existing theoretical models. Figure 3.12b illustrates the gradient of velocity component  $u_x$  of the airflow around the grid opening. Within the grid opening, regions experiencing the wall effect exhibit large velocity gradients due to the presence of the boundary layer. The velocity gradient  $du_x/dy$  is cast into non-dimensional form as  $d\bar{u}_x/d\bar{y}$  by letting  $\bar{u}_x = u_x/u_0$  and  $\bar{y} = y/l_{sp}$  to compare four different fiber grids with  $\delta = 4, 64$  and  $\chi = 0.6, 60$ . At a fixed velocity of  $u_p = 0.5 \text{ m s}^{-1}$ , the area of a greater velocity gradient around the fiber grid of  $\delta = 4$  and  $\chi = 0.6$  extends to a larger distance compared to other fiber-grid geometries, indicating a stronger wall effect on the airflow penetrating the grid opening. In addition, the velocity profile along the centerline of grids (see Figure 3.12c) shows that the grids with  $\delta = 4 \chi = 0.6$ ,  $\delta = 4 \chi = 6$ , and  $\delta = 16 \chi = 0.6$  have a parabolic velocity profile across the grid opening centerline, i.e., the Poiseuille profile, suggesting a dominant viscous diffusion of momentum due to the interacting thick boundary layers. In contrast, the grids with larger  $\delta$  or  $\chi$  generally have a uniform velocity profile for  $-0.4 < \bar{y} < 0.4$ , suggesting a dominant inertial advection in the mainstream. Therefore, the airflow penetrating dense thin-fiber grids is subject to wall effect due to the interacting thick boundary layers.

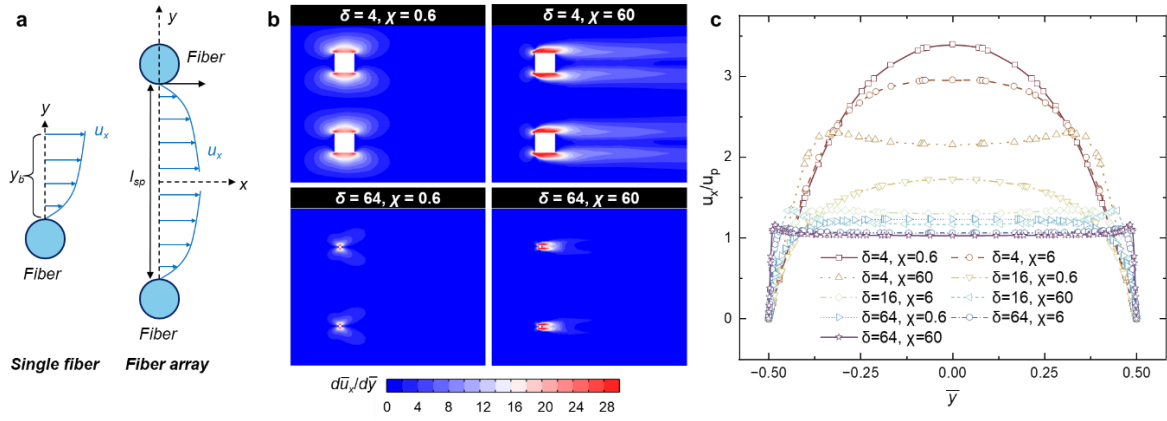


Figure 3.12. Wall effect of the fiber grids due to the interacting boundary layers. (a) Schematics of thick boundary layers around a single fiber with a small Reynolds number and interactions between fiber boundary layers in a fiber array. (b) The wall effect around fiber grid openings according to the results of the present simulation. The colored contours indicate the velocity gradient of the airflow. (c) Velocity profile over the fiber-grid opening across the centerline of the grid for different geometries.

The wall effect enhances the drag of airflow exerted on the grid. As shown in Figure 3.13a, the drag coefficient of  $C_D = F_D/(0.5\rho u_p^2 A)$  is correlated to the fiber Reynolds number  $Re_f = \rho u_p d_{\text{fiber}}/\mu$  for grids with  $\delta = 4 - 64$  and  $\chi = 0.6 - 60$ , where  $A$  is the projected area of fibers. The drag coefficient  $C_D$  rises with decreasing  $Re_f$  when the flow regime transits to creeping flow at  $Re_f < 1$  because the thickened boundary layer due to smaller fiber diameter and flow velocities enhances viscous dissipation of fluid momentum. Specifically, the increment of  $C_D$  at  $Re_f < 1$  decreases with increasing spacing  $\delta$  from 4 to 64 as a result of suppressed interaction of boundary layers around distanced boundaries. Notably, the  $C_D$  of the dense thin-fiber grids with  $\delta = 4$  and 8 reaches 200 and 70 at  $Re_f = 0.1$  and is considerably larger than solid plate structures with  $C_D < 8$ , which is consistent with published experiments [77]. Therefore, the wall effect due to small  $\delta$  and  $\chi$  leads to a strong viscous drag on the grids.

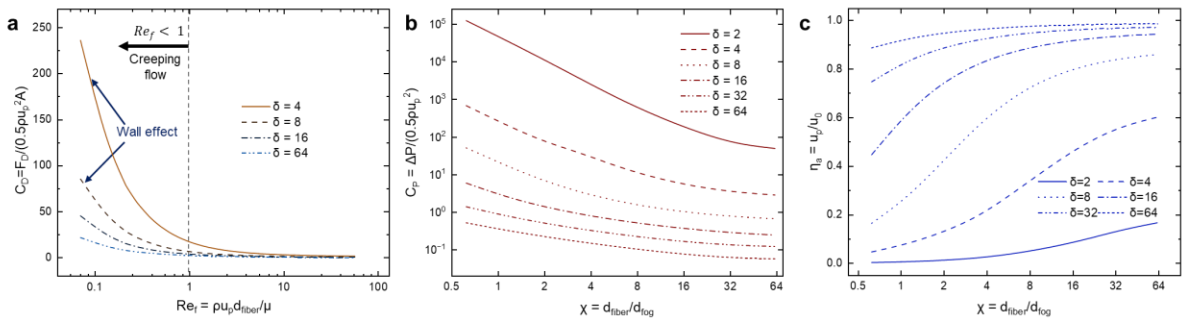


Figure 3.13. Wall effect on drag, pressure loss coefficient and penetrating ratio. (a) Airflow drag coefficient as a function of the fiber Reynolds number. (b, c) Pressure loss coefficient  $C_p$  and ratio of the penetrating airflow  $\eta_a$  at different fiber diameters and spacings.

The elevated drag creates a greater pressure drop over the collector, resulting in more fog flow circumventing the collector instead of passing through it. As shown in Figure 3.13b, the

pressure loss coefficient of collectors  $C_P$  calculated by the full-size model shows a similar trend as the drag coefficient, where the fiber grids with a small  $\delta$  and  $\chi$  generate a higher  $C_P$ . Consequently, the airflow tends to circumvent the grids and thus causes a reduced penetrating airflow ratio  $\eta_a$  (see Figure 3.13c), which explains the loss of the overall efficiency  $E$ . In the experimental study in Chapter 4 [78], the overall efficiency of the dense micro-fiber grids with  $\delta = 5-10$  and  $\chi = 0.625$  is 12-15%, which is lower than  $E$  ( $\sim 20\%$ ) obtained using the sparse grids with  $\delta = 20-50$  and  $\chi = 0.625$ , indicating the negative influence of wall effect on collection efficiency. Therefore, the reduction in collection efficiency for  $\delta < 16$  and  $\chi < 8$  is caused by the airflow circumventing the collector due to the wall effect of the dense thin-fiber grids.

### 3.3.4 Positive clogging on sparse thin-fiber grid

The overall collection efficiency of a clogged grid is affected by the interaction of three factors – projected area, Stokes number, and pressure loss. During the growth of clogging drops, as shown in Figure 3.14a, the drop first provides a larger projected area to improve the ratio of captured fog droplet  $\eta_b$  compared to a bare fiber. However,  $\eta_b$  decreases as the drop radius  $r_c$  further grows because the challenge droplets tend to pass around the drop at a reduced Stokes number. Furthermore, the enlarged projected area increases the pressure loss over the grid, leading to a reduced  $\eta_a$ . Specifically, fog diameters of  $d_{fog} = 16 \mu\text{m}$  and  $32 \mu\text{m}$  in Figure 3.11g and i lead to a sufficiently high Stokes number that “saturates” the deposit efficiency  $\eta_b$ , whereas the smaller  $d_{fog}$  of  $8 \mu\text{m}$  in Figure 3.11h reduces the Stokes number and  $\eta_b$ . Meanwhile, clogging on sparse and thin-fiber grid provides an increased projected areas while maintaining a lower pressure loss compared to the dense grids, leading to a positive effect on collection efficiency. Together, clogging on sparse thin-fiber grids increases the projected area, which dominates the interaction of the three factors and leads to a positive clogging effect.

The positive clogging effect is first examined at the fixed  $\varphi = 0.63$  and  $d_{fog} = 16 \mu\text{m}$  as introduced in Section 3.3.2. Compared to the bare grids, clogging at  $\varphi = 0.63$  increases the projected area fraction  $SC$  (see Figure 3.14b) by a factor of 3.2 - 10.7 for the sparse grids with  $\delta = 16 - 64$ ; clogging on the dense grids with  $\delta = 2 - 8$  increases  $SC$  by a smaller factor of 1.1-2.0. Meanwhile, Figure 3.14c illustrates that the pressure loss coefficient  $C_P$  of the sparse grids with  $\delta = 16 - 64$  ranges from 0.3 to 28.4, which is lower than that of the dense grids with  $\delta = 2 - 8$ . The smaller  $C_P$  indicates a greater  $\eta_a$  in the range of 0.22 - 0.92, which ensures more challenge droplets approaching collector compared to the dense grids. In addition, Figure 3.14d shows that thinner fibers with  $\chi < 6$  suppress the clogging Stokes number  $Stk_c$  which decreases

with increasing  $\delta$  because the clogging radius  $r_c$  at a fixed  $\phi$  is less than that of thicker fibers. Therefore, the positive clogging effect is based on the increased projected area while maintaining a low pressure drop and a large Stokes number.

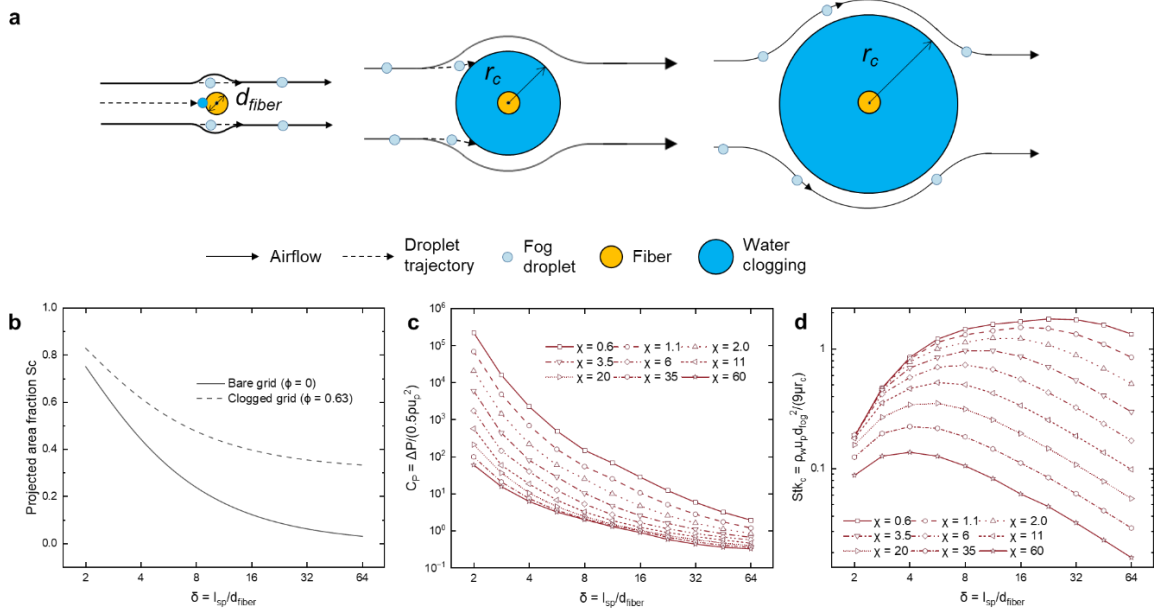


Figure 3.14. Positive clogging effect of sparse thin-fiber grids. (a) Schematics of droplet capture on a fiber and a drop attached to the fiber during the growth of the drop. (b) Calculated projected area fraction  $Sc$  as a function of fiber spacing  $\delta$  for the bare grid ( $\phi = 0$ ) and clogged grid ( $\phi = 0.63$ ). (c-d) Pressure loss coefficient  $C_p$  (c), and clogging Stokes number  $Stk_c$  (d) as functions of  $\delta$  for  $\chi = 0.6-60$  and  $\phi = 0.63$ .

Considering that the growth of clogging is a dynamic process, the collection efficiency  $E$  is investigated for  $\phi$  varying from 0 to 1. As shown in Figure 3.15, four distinct grid geometries are selected to compare their collection efficiency under bare and clogged conditions. The chosen geometries are  $\delta = 4$  and  $\chi = 3$ ,  $\delta = 20$  and  $\chi = 3$ ,  $\delta = 4$  and  $\chi = 16$ ,  $\delta = 20$  and  $\chi = 16$ , representing grids with dense/sparse spacings and thin/thick fibers. As clogging grows from the bare condition ( $\phi = 0$ ), the efficiency of the clogged grid,  $E_{\text{clog}}$ , with  $\delta = 20$  and  $\chi = 3$  increases to 1.3 times that of the bare grid,  $E_{\text{bare}}$ , then decreases to  $E_{\text{clog}}/E_{\text{bare}} = 0.6$  at  $\phi = 1$ . In contrast, the efficiency of the other three geometries decreases to  $E_{\text{clog}}/E_{\text{bare}} < 0.2$  at  $\phi = 1$ . Therefore, the sparse thin-fiber grid (i.e.,  $\delta = 20$ ,  $\chi = 3$ ) collects fog droplets better when clogged by waterdrops with  $0 < \phi < 0.7$  and prevents the efficiency loss at  $\phi > 0.7$  better than the other geometries.

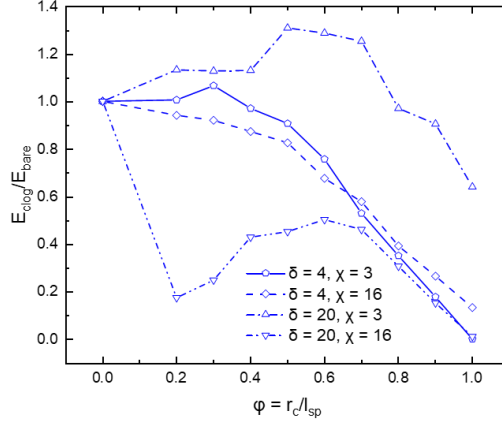


Figure 3.15. Ratio of  $E_{clog}$  to  $E_{bare}$  for four grid geometries during the growth of clogging drops from  $\phi = 0$  to 1.

Figure 3.16a-c maps the positive and negative effects of clogging for different grid structures at  $\phi=0.2, 0.4$ , and  $0.63$ . The positive clogging region of  $E_{clog}/E_{bare} > 1.2$  first appears as a narrow band between  $\delta = 10$  and  $\delta = 20$  at  $\phi = 0.2$ . As  $\phi$  increases to  $0.4$  and  $0.63$ , the clogging provides more projected area to capture droplets. As a result, the region gradually spreads towards the upper left, forming a triangular region bounded by three points of geometries ( $\delta = 10, \chi = 0.6$ ), ( $\delta = 64, \chi = 0.6$ ), and ( $\delta = 10, \chi = 32$ ). In addition, the efficiency of the region on the upper right shows a rapid efficiency loss of  $E_{clog}/E_{bare} < 0.6$  when clogged, which is caused by the dominance of the Stokes number effect due to the excessively large radius  $r_c$  of the clogging drops. Therefore, two distinct clogging effects exist for the sparse grids with  $\delta > 10$  and are partitioned by a line connecting ( $\delta = 64, \chi = 0.6$ ) and ( $\delta = 10, \chi = 32$ ). Overall, clogging drops on a thin and sparse grid enhances the water collection efficiency.

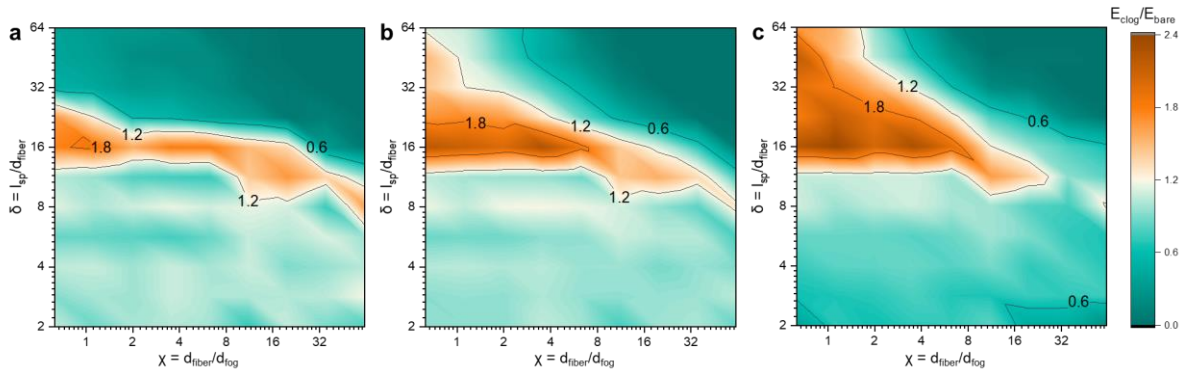


Figure 3.16. Mapped positive and negative effects of clogging for  $\phi = 0.2$  (a),  $0.4$  (b), and  $0.63$  (c) based on  $E_{clog}/E_{bare}$  for fiber grids with  $\delta = 2 - 64$  and  $\chi = 0.6 - 60$ .

### 3.3.5 Connected clogging ( $\phi > 1$ ) on thin-fiber grids

The preceding results show the effect of clogging on overall efficiency when the clogging drops are smaller than the fiber spacing. The conclusion holds for fiber grids with larger

diameters and openings, where clogging tends to have difficulty spreading to multiple openings due to surface tension. However, previous studies show that the waterdrop on finer grids can grow larger than the fiber spacing to clog neighboring openings [20]. Therefore, the effect of such connected clogging on the collection efficiency deserves further investigation.

The connected clogging forms when the maximum radius of the clogging exceeds the fiber spacing, i.e.,  $\varphi > 1$ . The maximum size of clogging depends on whether the gravity to shed the drop from the surface can overcome the adhesion force. Here, Bond number is used to characterize the relative scale of the gravitational force and adhesion. The Bond number  $Bo$  is expressed as

$$Bo = \frac{\rho_w g r_c^2}{\gamma} \quad (75)$$

where  $g$  is the gravitational acceleration, and  $\gamma$  is the surface tension of the waterdrop. However, the preceding form of  $Bo$  excludes the effect of fiber grid geometries on waterdrop adhesion. Considering that the waterdrop can only adhere to the solid fraction of the grids,  $Bo$  can be modified by adding the projected area fraction  $SC$  to the denominator as follows [184].

$$Bo = \frac{\rho_w g r_c^2}{\gamma SC} = \frac{\rho_w g r_c^2 \delta^2}{\gamma (2\delta - 1)} \quad (76)$$

The modified Bond number divides the fiber geometries into two classes based on whether the clogging connects. Depending on surface wettability and roughness, the shedding of waterdrop takes place at different Bond numbers. Let us first consider that the clogging drop can be shed at a critical bond number of  $Bo_c = 1$ . As shown in Figure 3.17a, the geometry of fiber grids is partitioned by a line that indicates the drop radius is equal to the fiber spacing, i.e.,  $\varphi = 1$ . As a result, the clogging regime on fiber grids is divided into two categories: the dispersed clogging where  $\varphi < 1$ , and the connected clogging where  $\varphi > 1$ . Notably, the dense thin-fiber grids with smaller  $\chi$  and  $\delta$  are subjected to the influence of connected clogging. In addition, the line is shifted to the left or the right by assuming that the shedding takes place at different critical Bond numbers of  $Bo_c = 0.2$  and  $Bo_c = 5$ , which can be practically achieved by adjusting the wettability of fiber surface. The shifting changes the range of fiber grids that are subjected to the influence of connected clogging. Therefore, the formation of connected clogging with  $\varphi > 1$  is determined by the critical Bond number of a drop when it is shed from the grid.

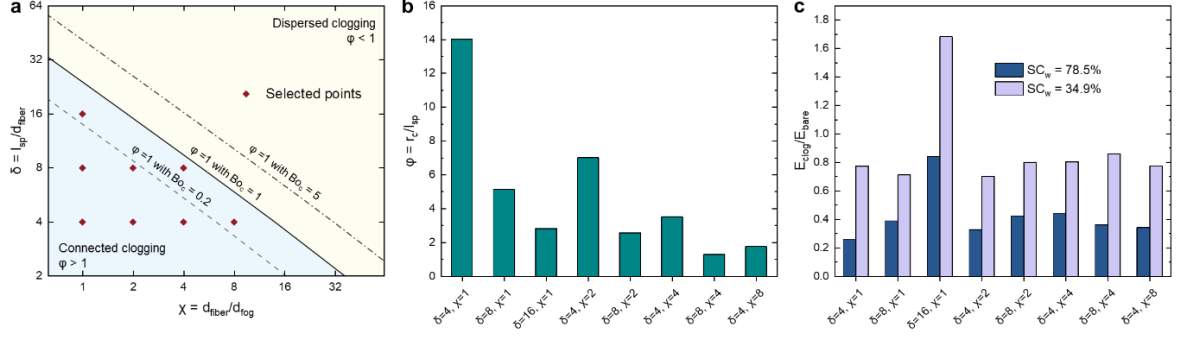


Figure 3.17. Connected clogging on thin-fiber grids. (a) Fiber grid geometry divided by  $\phi = 1$  into connected clogging region ( $\phi > 1$ ) and dispersed clogging region ( $\phi < 1$ ). (b) Maximum size of connected water clogging calculated using the critical Bond number  $Bo_c = 1$ . (c) Ratio of  $E_{clog}$  to  $E_{bare}$  for eight distinct grids clogged by maximum size of connected clogging.

Using the critical Bond number  $Bo_c = 1$ , the maximum size of the connected water clogging is determined before the drop shedding. Eight distinct grid geometries are selected from the connected clogging region in Figure 3.17a, representing 3 levels for  $\delta$  and 4 levels for  $\chi$ . The selected points vary in distance from the partition line. As shown in Figure 3.17b, the grid with  $\delta = 4$  and  $\chi = 1$  has the largest clogging size of  $\phi = 14$ , and the grid with  $\delta = 8$  and  $\chi = 4$  has the smallest clogging size of  $\phi = 1.3$ . Therefore, the magnitude of  $\phi$  is determined by the distance between the selected point and the partition line.

The maximum clogging size is then used to evaluate the effect of connected clogging on collection efficiency at a fog diameter  $d_{fog} = 16 \mu m$ . The projected area fraction of drops  $SC_w = \pi r_c^2 / (n l_{sp}^2) = \pi \phi^2 / n$  is introduced to quantify the coverage of the connected drops, where  $n$  is the number of openings for the simulated grid unit in the close-up model. As shown in Figure 3.17c, the connected clogging generally reduces the overall efficiency. For the seven selected grid geometries except  $\delta = 16, \chi = 1$ ,  $E_{clog}/E_{bare}$  is in the range of 0.7-0.8 when  $SC_w = 34.9\%$ , and in the range of 0.25-0.4 when  $SC_w = 78.5\%$ . Notably, the overall efficiency loss is more dependent on clogging coverage  $SC_w$  than on the grid geometry  $\delta$  and  $\chi$  or the single clogging size  $\phi$ , which results from the dominating effect of the pressure loss. In contrast, the sparse thin-fiber grid with  $\delta = 16$  and  $\chi = 1$  maintains a high efficiency when clogged. This geometry has an  $E_{clog}/E_{bare}$  value of 1.7 at  $SC_w = 34.9\%$  and 0.8 at  $SC_w = 78.5\%$ , both higher compared to the other seven geometries. Therefore, the connected clogging generally reduces the collection efficiency based on the projected area fraction of drops; the sparse thin-fiber grids are the most enduring to connected waterdrop clogging.

### 3.3.6 Mapping effects on collection efficiency for new design rubrics

Figure 3.18 maps the effects of fiber geometries and clogging on water collection efficiency. Specifically, the lower left region for  $\delta = 2-16$  and  $\chi = 0.6-8$  is subject to the influence of the wall effect that increases pressure loss compared to grids with thicker fibers and wider spacings. In addition, the upper left region bounded by two lines of  $\delta = 16$  and  $\delta = 54/\chi^{0.35}$  is subject to a positive clogging effect following the simulation results for  $d_{\text{fog}} = 16 \mu\text{m}$  and  $32 \mu\text{m}$ . The collection efficiency of fiber grids in this region can benefit from clogging, which is validated by the experimental study of micro-fiber grids in Chapter 4. It is noticed that positive clogging does not prevail for  $d_{\text{fog}} = 8 \mu\text{m}$ . However,  $d_{\text{fog}} = 16 \mu\text{m}$  gives a reasonable average droplet diameter considering (a) droplet diameter normally follows a logarithmic-normal distribution within a range of  $2-50 \mu\text{m}$  [17, 19, 22], and (b) large and heavy fog droplets contribute the most to the efficiency. The upper right region bounded by the lines of  $\delta = 16$  and  $\delta = 54/\chi^{0.35}$  is subject to the negative effect of clogging, which rapidly reduces the overall collection efficiency upon the formation of water clogging. Furthermore, connected clogging can form when the maximum radius of shedding drops exceeds the fiber spacing, reducing the collection efficiency of the collector. In contrast, the prior-art fog collector geometry [12, 20, 80, 154, 162, 168] is concentrated in the lower right region, where the fibers are thicker and more narrowly spaced, complying with the existing theories and design rubrics. Therefore, this study extends the state-of-the-art knowledge of fog harvesting using thin-fiber grids.

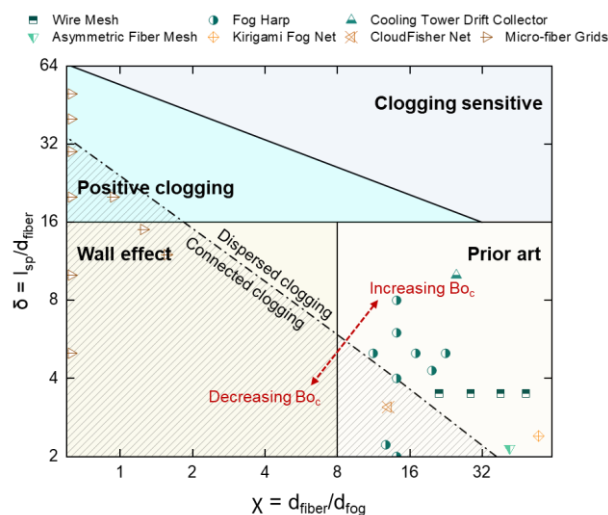


Figure 3.18. Map that summarizes the effects investigated in this study across geometries of thin-fiber grids, including the regions of wall effect, positive clogging, clogging sensitive, as well as the partition for connected clogging. Geometrical parameters of existing fog collector designs [12, 20, 78, 80, 154, 162, 168], shown as the Prior art region, are provided for comparison.

The mapped effects provide insights into the geometrical design and drainage capability of thin-fiber fog collectors. First, the wall effect should be avoided to let more fog-laden airflow pass through the collector. Minimizing the wall effect relies on practical measures that increase the fiber Reynolds number to suppress the interaction of boundary layers, such as using a thicker fiber diameter of  $\chi > 8$  and a wider spacing of  $\delta > 16$ , as well as deploying the collector in the area with higher wind speed. Second, the positive clogging effect is an intriguing feature of sparse thin-fiber grids, which can be used when the application requires stable collection efficiency even when the grid is severely clogged due to a heavy-load fog flow or lack of shed forces, such as the inclined arrangement of collectors in industrial cooling towers [7, 162]. Third, the connected clogging effect should be minimized. Based on the simulation results, two strategies are effective in suppressing the connected clogging effect, including (a) reducing the critical Bond number of drop shedding to prevent the formation of connected clogging, and (b) enhancing the shedding frequency of waterdrops to reduce the coverage of connected clogging. The former relies on surface treatment or modification to shed the drops at a smaller radius; however, the critical shedding radius should be carefully controlled so that early tiny drops can attach to the surface instead of being re-entrained. The latter strategy requires a fast growth of waterdrops to their critical shedding size, which can be achieved using fibers with liquid transport abilities that accelerate the coalescence of drops [25-27, 185].

It should be noted that the map can be extended to harp-style collectors. Harp-style arrangement of fibers can effectively remove the clogging by eliminating the horizontal fibers to reduce the pinning force on waterdrops. Considering the absence of horizontal fibers, the preceding map can be modified using a new dimensionless spacing of  $\delta_m = 2\delta$  to maintain the same  $SC$ , developing the design rubrics of harp-like collectors.

### 3.4 Summary

In summary, this study numerically investigates fog water collection efficiency of thin-fiber grids. The fog harvesting process is modeled at two scales, i.e., collector scale and fiber scale, and the two scales are coupled together through pressure loss coefficient and ratio of captured water droplets. The result reveals two important effects on collection efficiency – the wall effect and positive clogging effect. The wall effect increases pressure loss in the dense thin-fiber grid due to the interaction of thick boundary layers, leading to a reduced penetrating airflow and overall efficiency. The positive clogging enhances droplet capture capability of the sparse thin-fiber grids by providing a larger projected area. The studied effects are mapped

according to the geometry of fiber grids, which provides new insights into the geometrical design and drainage capability of novel fog collectors. This work extends the current theories of fog harvesting by introducing the wall effect and positive clogging effect and shapes new rubrics for fog collector design.

Furthermore, this study has the following limitations that require further investigation based on the current results. First, this study simulates a uniform waterdrop distribution across the fiber grid, whereas the practical size of waterdrops is normally polydisperse considering the random occurrence of shedding and coalescence. Therefore, the effect of polydispersity of waterdrop size on water collection efficiency requires further investigation. In addition, the critical Bond number  $Bo_c$  for waterdrop shedding requires an in-depth study that anchors the relationship between  $Bo_c$ , surface wettability, and grid structure to better predict collection efficiency of clogged fibers and to better design collector geometries. Moreover, the loss of collection efficiency due to re-entrainment, i.e.,  $\eta_{dr}$ , is neglected in this study due to the low wind speed of  $1 \text{ m s}^{-1}$ . However, the re-entrainment of droplets is relatively important at a higher wind speed and superhydrophobic fibers, thus requiring further investigations.

## Chapter 4 Waterdrop-assisted Droplet Capture on Micro-fiber Grids\*

From Chapter 3, the positive clogging effect of fiber grid geometry on collection efficiency is found by numerical simulation. The positive clogging effect is promising in terms of using thin and sparse fiber grids to effectively capture fog droplets, while maintaining a relatively high collection efficiency when severely clogged. However, the preceding conclusion is based on a simplified numerical model, where the size of clogging drops is assumed to be uniform across the collector surface. In practice, the size and distribution of waterdrops varies during the harvesting process, because the drops dynamically grow and shed. Thus, the clogging effect on droplet capture and collection efficiency should be investigated in practical situations. In addition, the feasibility of using the positive clogging effect to develop efficient fog collectors should be evaluated experimentally. Therefore, this chapter focuses on experimentally investigating the positive clogging effect for developing efficient fog collectors.

### 4.1 Introduction

Fog harvesting is an opportunity to overcome the challenge of water shortage using fog collectors to capture water droplets from natural fog or industrial plumes. Fog collectors based on Polyethylene-based Raschel meshes have been deployed to collect fog water at coastal mountains [14], highlands [15, 16], and industrial cooling towers [7]. However, the Raschel mesh suffers from the low collection efficiency, especially at low windspeeds [12, 14]. Therefore, efficient fog collectors are needed to better harvest fog water.

Researchers modified the structure and surface property of fog collectors to improve the water collection efficiency. Figure 4.1a summarizes a diagram based on the obstacle size of the collector. Interestingly, most structures with the size of  $>1000\ \mu\text{m}$  improves the collection efficiency by increasing the chance of the fog droplets depositing on the obstacle. For example, Li et al. used a pyramidal kirigami structure with a feature size of 5~10 mm to collect fog droplets [181]. The kirigami structure induces air vortices, which enhances the capture of fog by aggregating droplets in the vortex core. On the other hand, the structure with a size of 100~1000  $\mu\text{m}$  normally requires high capability of water transport to reduce water clogging. For example, Shi et al. developed a fog harp collector with vertically aligned fibers of 250  $\mu\text{m}$

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\* The contents in this chapter have been published in *Chemical Engineering Journal* 481: 148423.

diameter and 0.5 mm spacing, which reduces the pinning force acting on waterdrops [20]. The design improves water transport to reduce clogging, leading to a collection efficiency three times higher than conventional square grids.

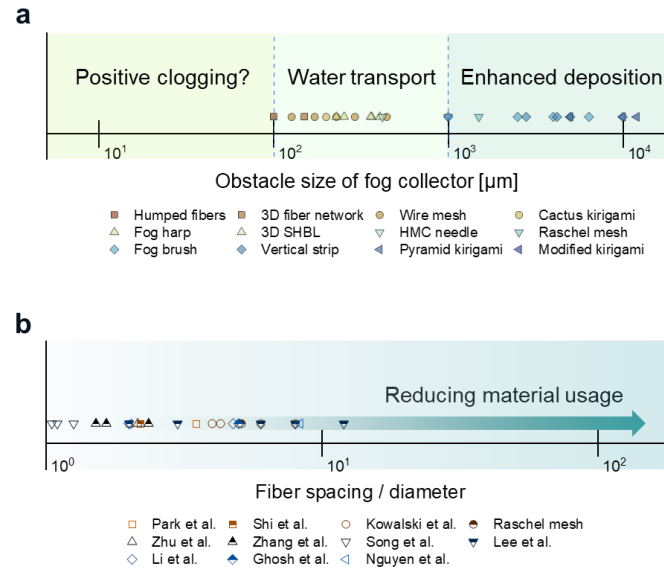


Figure 4.1. Summary of prior works of fog collectors. (a) Summarizing prior fog collectors based on their obstacle sizes. (c) Summarizing reported fog collectors with fiber-grid structure based on the ratio between fiber spacing and fiber diameter. The size information in (a) and (b) is obtained from references [12, 20, 29, 33, 56, 59, 70, 80, 154, 162-165, 181, 186-190].

Reducing the obstacle size down to micrometer level is necessary from both a theoretical and a practical perspective. First, the existing works are centered on obstacle size from several hundred micrometers to centimeters. However, the positive clogging effect [191] has been found in numerical simulation presented in Chapter 3, increasing the collection efficiency for sparse and thin fiber grids. Second, as shown in Figure 4.1b, most reported fiber-grid collectors are based on thick fibers and dense grids with a ratio between fiber spacing and diameter of 1~10, suggesting a high material usage. In contrast, fiber-grid structures with small fiber diameters and wide fiber spacing are desired, thereby reducing the material usage for fabricating fog collectors. Therefore, collectors based on fiber-grid structure with micrometer-level diameter require further investigation.

To fill the preceding gaps, this study investigates the capture of fog droplets by waterdrops on microfiber grids fabricated with near-field electrospinning (NFES). The result shows that, on micro-fiber grids, the captured fog water appears as waterdrops with a wide range of size distribution and clogs the grid opening. Due to the small fiber diameter ( $\leq 25 \mu\text{m}$ ), small waterdrops are “visible” to airflow, thus effectively capturing fog droplets. In addition, large waterdrops deflect the fog-carrying airflow to the satellite small waterdrops, further enhancing

the droplet capture. As a result, the microfiber-based fog collectors effectively collect fog water without involving any special chemical modification or surface texture to enhance waterdrop shedding. The collection efficiency is record high (at 21.4%) compared to fog collectors based on thick fibers (max of 17%) [80], because the thick fibers shade the small waterdrops thus losing the capability of small waterdrops to capture fog droplets. Therefore, the micro-fiber fog collector shows an exciting potential of application due to its high collection efficiency from the assistance of clogging waterdrops.

## 4.2 Experiment

### 4.2.1 Fabrication and characterization of micro-fiber grids

#### *Solution preparation*

2.5 g Poly(vinylidene fluoride-co-hexafluoropropylene) (PVDF-HFP, Mw ~ 455,000, Sigma Aldrich, Canada) is dissolved into a mixture solvent of 3.75 g *N,N*-dimethylacetamide (DMAc, purity > 99.8%, Sigma Aldrich, Canada) and 3.75 g acetone (purity  $\geq 99.5\%$ , Fisher Scientific, Canada) to prepare a PVDF-HFP solution of 25 wt% concentration. The solution is stirred overnight at room temperature.

#### *Near-field electrospinning*

A near-field electrospinning system (see Figure 4.2a-c) is used to fabricate micro-fiber grids. The fabrication process begins by loading the prepared PVDF-HFP solution into a glass syringe equipped with a 26 gauge metallic needle, which is connected to the high-voltage power supply (ES30, Gamma High Voltage Research, USA). A syringe pump (LEGATO 100, KD Scientific, USA) delivers the solution at a flow rate of  $50 \mu\text{L h}^{-1}$  to the needle tip. A piece of non-stick aluminum foil (Reynolds wrap, USA) is securely fixed on a X-Y stage (XMS-100, Newport Inc., USA) and grounded as the fiber collector. The distance between the needle tip and the collector is maintained at 1.5 mm. A voltage of 1.6kV is applied on needle to initiate an electrohydrodynamic jet of the solution that deposits on the collector and dries into fibers. A microscopic camera (Phantom Miro eX2, Vision Research, Inc., USA) is used to monitor the jet. The motion trajectory of X-Y stage is programmed using LabView software (NI, USA) to pattern the deposition of fibers, which is introduced in Appendix B. The patterned microfibers on the aluminum foil are left to dry at room temperature for 24 hours or longer.

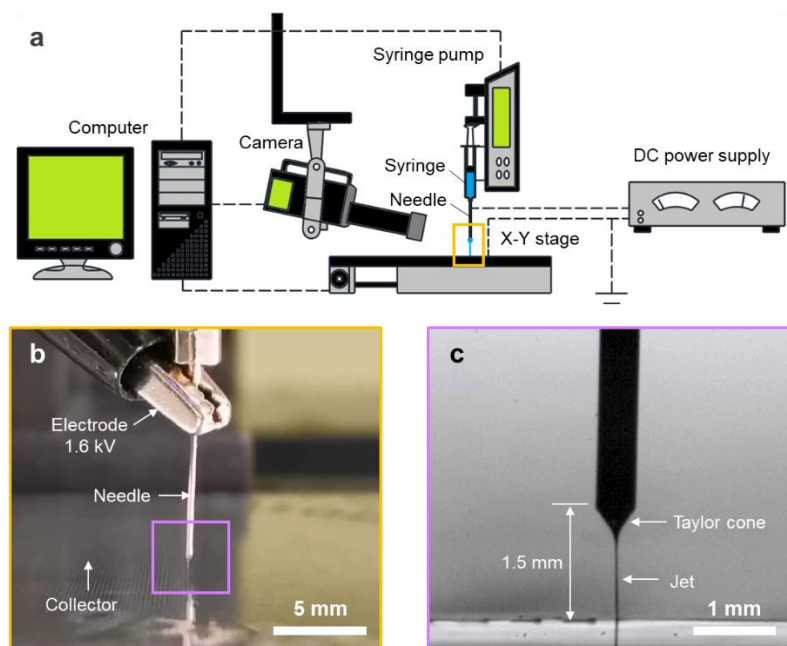


Figure 4.2. Near-field electrospinning (NFES) system to fabricate micro-fiber grids. (a) Schematic of the experimental setup of the NFES system. (b) Close-up image of the syringe needle connected to an electrode charged with a 1.6 kV voltage. (c) Microscopic image of Taylor cone and electrohydrodynamic jet formed during the operation of NFES.

### *Assembly of fog collectors*

Fog collectors are assembled in the following steps: First, adhesives (double-sided scotch, 3M) are applied to two copper gaskets with an internal diameter of 36.83 mm (CF-275-GA-CO, ANCORP, USA) to provide adhesive surfaces. Subsequently, one gasket with an adhesive surface is pressed onto the fiber grid deposited on the aluminum foil. The aluminum foil is then carefully peeled off, leaving the fiber grid securely adhered to the gasket. Finally, the other copper gasket is affixed to the gasket with fibers to prevent exposure of the adhesives.

### *Fiber characterization*

The morphology of samples and their geometrical parameters are characterized using both optical and electron microscopy techniques. First, the fabricated collector samples are examined under a digital microscope (SW380B and SC1603, Swift Microscope, USA) to observe the fiber direction and patterns. Second, the morphology of the fibers and fiber connections is characterized using a scanning electron microscope (SEM, UltraPlus FESEM, Zeiss, Germany) after sputtering with a thin layer of gold for 120 seconds. Optical and SEM images are analyzed using software (ImageJ, NIH, USA) to measure the fiber spacing and the diameter of individual fibers.

#### 4.2.2 Water collection test

Water collection test is conducted in a closed chamber (width 74 cm, length 68 cm, height 54 cm), which avoid the disturbance of lab environment [12, 20, 80, 158, 192, 193]. As shown in Figure 4.3, an ultrasonic humidifier (Inkbird, China) atomizes deionized water to fine fog droplets with diameter of  $16.06 \pm 8.24 \mu\text{m}$ , which are carried by the airflow from the humidifier to exit the fog nozzle at a fog flow rate of  $55\sim 180 \text{ g h}^{-1}$ . A fiber grid is placed 5 cm away from the nozzle outlet to receive the fog flow at a velocity of  $0.45 \text{ m s}^{-1}$ . The distance of 5 cm is set up to allow the cross section of unperturbed fog flow (free-flowing flow without the blockage of fiber grid) to coincide with the fiber grid area. This ensures sufficient coverage of fog flow, while avoiding capturing fog droplets that would have circumvented the collector. A stereo microscope (AmScope, USA) and a high-speed camera (Phantom Miro eX2, Vision Research, Inc., USA) are placed at the rear side of the grid to measure the projected area, diameter and spacing of the waterdrops. The collected water is gathered in a glass beaker, which is weighed using an analytical scale to measure the mass of collected water.

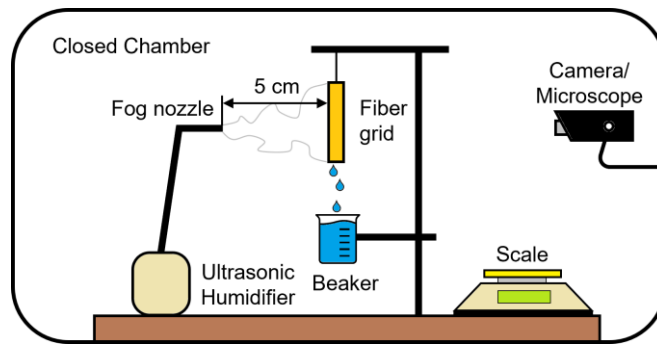


Figure 4.3. Schematic of experimental setup for water collection test.

Fog weather in an actual environment is formed when the ambient air temperature falls below the dewpoint of the humid air, leading to the condensation of fog droplets [194]. As a result, the humidity of fog flow is normally saturated at the respective ambient temperature. To simulate the actual environment, the temperature and humidity of the chamber are monitored by a hygrometer (597C1, TPI, Canada) and maintained at room temperature and saturation.

The collection efficiency of collectors is measured at the maximum fog flow ( $Q = 180 \text{ g h}^{-1}$ ). Using the maximum fog flow allows measuring the weight of collected water more precisely due to the larger mass of water flux. The collected fog water drains from the collector into a beaker, which is weighed using an analytical scale to measure the mass of collected water. The water collection amount is measured every 10 minutes consecutively for 1 hour during

each test; every collector sample is tested 3 times and the results are averaged as the water collection per hour,  $q_c$ . The collection efficiency  $E$  for each sample is calculated as follows.

$$E = Q_c/Q \quad (77)$$

### 4.2.3 Characterizing fog condition

To evaluate the water collection capability of micro-fiber grids, the fog condition generated by instrument should be characterized. Three parameters representing the fog condition, i.e., flow rate of fog water, airflow velocity and fog droplet diameter, are measured as follows.

#### *Fog water flow rate*

The flow rate of fog water generated by an ultrasonic humidifier is measured by a method of weight reduction as follows. First, the humidifier loaded with deionized water is placed in a closed chamber at saturated humidity. The weight of the humidifier is measured as  $w_1$  using a balance. Then, the humidifier is operated at a steady output for 15 minutes and turned off for weighing, which is recorded as  $w_2$ . The net flow rate of fog water is then calculated as

$$Q = \frac{w_1 - w_2}{15 \text{ min}} \quad (78)$$

The measurement is repeated 4 times to take the average value as the flow rate of fog water.

#### *Airflow velocity*

The humidifier outputs fog water by airflow. An indirect and non-intrusive method is used to measure the airflow velocity to avoid the influence of intrusive instruments on the airflow. Measurement of airflow velocity is conducted at the location where fiber grids are installed, and the velocity is measured without the grid. First, the airflow velocity at the nozzle outlet is measured by Space-time Image Velocimetry (STIV) [195]. The method was initially developed for analyzing the videos of rivers, where the ripples and waves generate textures on the image, which can be used to measure the velocity. Similarly, the fog flow also generates textures because of the uneven distribution of fog droplets or airflow vortices, allowing us to use the STIV to analyze the velocity of the fog flow. Specifically, a high-speed camera (Phantom Miro eX2, Vision Research, USA) is placed on one side of the fog nozzle, maintaining a perpendicular intersection between the direction of fog flow and the direction of vision. The humidifier outputs the fog flow to the nozzle, and the camera records a video of the fog flow for 6 seconds at a resolution of 640 x 480 pixel and a frame rate of 1200 fps with a scale of 23 pixel  $\text{mm}^{-1}$ . As shown in Figure 4.4a, the video is processed in ImageJ software to obtain a

Kymograph by vertically stacking a thin region of 570 pixels  $\times$  1 pixel over time axis. Analyzing the directionality of the texture in the Kymograph in ImageJ gives the angle of texture direction  $\psi$ , which is used to calculate the velocity in Equation (79).

$$u = \frac{l}{t} \tan \psi \quad (79)$$

where  $l$  is the unit length scale 0.043 mm pixel<sup>-1</sup>, and  $t$  is the unit time scale 8.33 $\times$ 10<sup>-4</sup> s pixel<sup>-1</sup>. The measurement is conducted in five thin regions, allowing taking the mean velocity across the fog flow. As a result, the fog velocity at the nozzle outlet is measured as  $u = 1.8 \text{ m s}^{-1}$ .

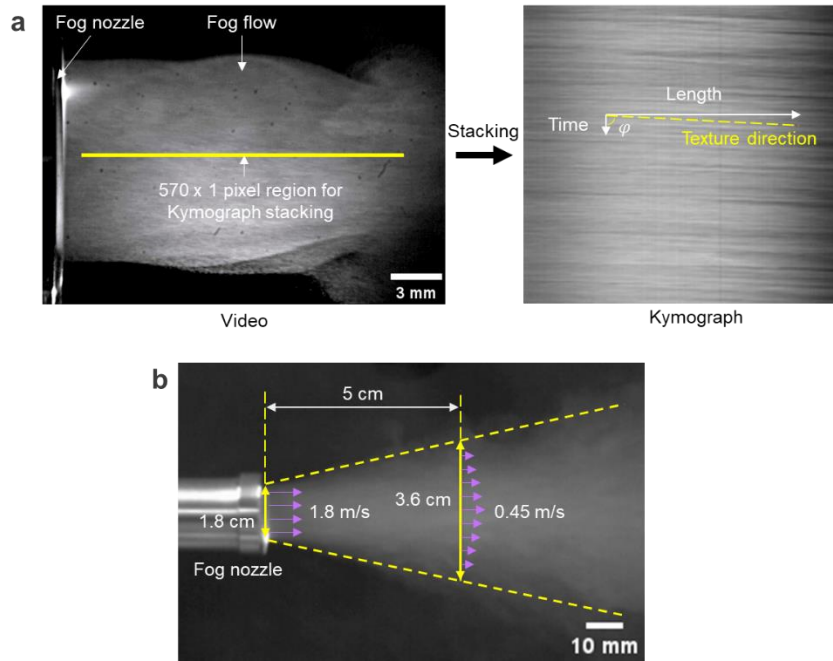


Figure 4.4. Methods to estimate the airflow velocity of the fog flow. (a) Processing a video of fog flow into a Kymograph by stacking a thin pixel region over time. (b) Digital image produced by stacking a six-second video of fog flow. The fog flow outlet the nozzle spreads from 1.8 cm to 3.6 cm at 5cm distance, gradually reducing the flow velocity from 1.8 m s<sup>-1</sup> to 0.45 m s<sup>-1</sup>.

Second, the velocity at the nozzle outlet is converted to a velocity 5 cm away from the nozzle where fiber grids are installed. Once away from the nozzle, the airflow jet diffuses to the surroundings, which reduces the velocity of the airflow. To estimate the velocity, a 6-second video of the fog flow is stacked into a time-averaged image to identify the spreading region of the airflow, as shown in Figure 4.4b. The image shows that the fog jet spreads to 3.6 cm at 5 cm away from the outlet, which is 2 times larger than the inner diameter of the nozzle (1.8 cm). The theory developed by Cushman-Roisin for expanding air jets [192, 196] is also used to examine the spread area of the fog flow; the theoretical calculation gives 3.8 cm, which

is close to the experimental value. Therefore, the airflow velocity  $u_0$  is estimated as  $0.45 \text{ m s}^{-1}$  in Equation (80).

$$u_0 \approx u \left( \frac{3.6}{1.8} \right)^2 = 0.45 \text{ m s}^{-1} \quad (80)$$

#### *Fog droplet diameter*

The diameter of fog droplets are measured following the immersion sampling method as follows [197]. First, a layer of silicone oil (Sylgard 184a, Dow, USA) is evenly applied on a glass slide. Second, the slide is placed 1 cm away from a working fog nozzle for 1 second. The droplets deposited on the slide sink into the oil due to density difference, and the oil coverage prevents the coalescence of droplets. The slide is then immediately placed under a microscope to record the image of fog droplets immersed in the silicone oil. The recorded images are processed using ImageJ software to statistically analyze the droplet diameter. The measurement is repeated five times. As a result, the fog droplet diameter follows a logarithm normal distribution (see Figure 4.5) with a mean diameter of  $16.06 \pm 8.24 \mu\text{m}$ .

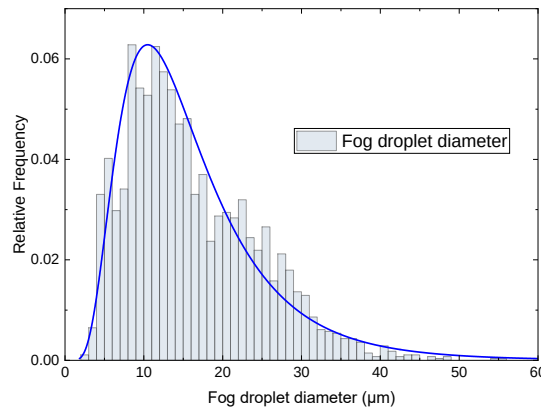


Figure 4.5. Statistical histogram of measured fog droplet diameter.

#### **4.2.4 Measurement of waterdrop size**

##### *Characterizing waterdrop clogging*

Water clogging is characterized by a digital camera (Phantom Miro eX2, Vision Research, Inc., USA) to measure 1) the projection area, 2) the size distribution, and 3) the spacing distribution of the waterdrops. The digital camera takes grayscale pictures of waterdrops every 5 minutes at a resolution of  $640 \times 480$  pixel and a scale of  $60 \text{ pixel mm}^{-1}$ . The obtained images are processed in ImageJ to analyze the dark region in the image, which is the projection area of waterdrops. In addition, the obtained images of waterdrops are used to analyze the

distribution of waterdrop size and spacing. The images are first processed to convert to binary images and remove the background fibers (see Figure 4.6). Specifically, the original image is converted to binary format by grayscale thresholding. The binary image is processed using the built-in functions of “OPEN” in ImageJ to remove the thin features in the image, i.e., the background fibers, while maintaining the original shape of waterdrops. Then, the processed images are analyzed using ImageJ to statistically measure the area of the waterdrops. Based on the area, the size distribution of waterdrops is calculated by treating the waterdrops as spheres. Moreover, the waterdrop spacing, which is the length of air gap between waterdrops, is analyzed using the ND plugin in ImageJ developed by Haeri et al.[198], which calculates the average distance from the edge of a waterdrop to the edge of its four nearest neighbors.

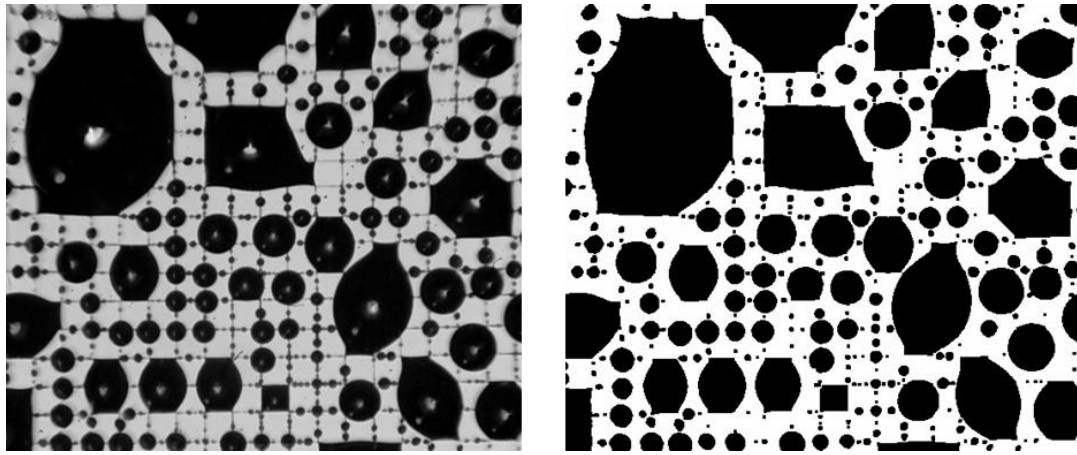


Figure 4.6. Image processing with ImageJ software for analyzing drop size.

#### *Measurement of waterdrop growth*

The growth of waterdrop is measured using an image-based method. First, a stereo microscope (AmScope, USA) is placed on the rear side to record the images of fiber grid surface. The microscope records the video of waterdrop growth at a frame rate of 3 fps and a magnification of 4x. The recording starts from the dry condition of a fiber grid and lasts for 30 seconds to avoid the shedding of waterdrops affecting the test results. Then, the recorded video is processed in ImageJ to analyze the change of waterdrop cross-sectional area over time. Using the area, the variation of effective shade coefficient and waterdrop volume can be calculated by treating the waterdrops as spheres.

### **4.3 Numerical simulation**

### 4.3.1 Physical Model

Droplet capture on waterdrops arrays is numerically simulated to understand the effect of the size difference and dispersion of clogging drops on droplet capture. Figure 4.7 depicts the physical model developed for numerical simulation. A penetrating airflow entrained with challenge droplets approaches a fiber grid with a velocity  $u_p$ . The grid contains an array of spherical waterdrops with radius of  $r_1$  and  $r_2$ , which are placed one mean waterdrop spacing,  $l_w$ , away from each other to simulate the polydisperse size and the spaced dispersion of waterdrops. Following the airflow penetrating the grid, the challenge droplets are either captured by the waterdrops or escape through the opening between the two drops; the fog droplets entrained in the circumventing airflow pass around the grid without being captured.

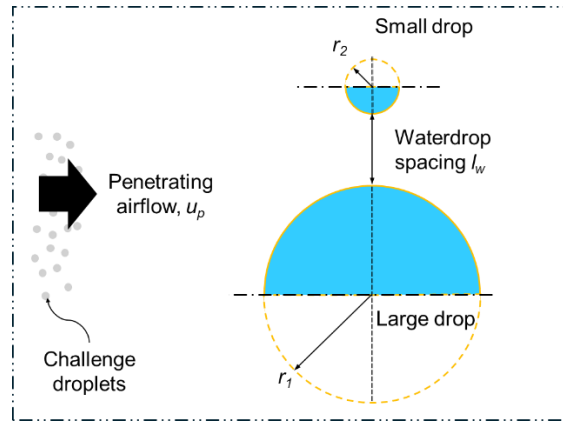


Figure 4.7. Schematics of the physical model developed for numerical study.

The fog droplets are modelled as particles that are subject to the drag force from the airflow, and the collection is simulated by tracing the movement of particles. First, a number of particles with a given diameter is released at the inlet boundary with the same velocity as the airflow. Then, the particles experience the drag forces from the airflow due to the velocity difference, which happens around the collector. Last, a particle is captured if its trajectory is intercepted by fibers or waterdrops.

### 4.3.2 Mathematical Formulation

#### *Governing Equations*

This study uses the laminar form of 2D Navier-Stokes equations to solve the velocity and pressure profiles. The airflow in collector is laminar due to the low Reynolds number (typically  $<100$ ) around the waterdrops and fibers. The motion of fog droplets released into the model domain follows Newton's second law. The details of the governing equations are given in Chapter 3 and not redundantly repeated in this section.

### Boundary and initial conditions

The boundary conditions for the system of differential equations are set up according to the boundaries numbered in Figure 4.8. The problem of fluid dynamics is solved at a steady state, which requires the following boundary conditions as inputs.

$$\text{Walls (4, 5)} \quad \mathbf{u} = 0 \quad (81)$$

$$\text{Air inlet (1)} \quad u_{\perp} = u_p, u_{\parallel} = 0 \quad (82)$$

$$\text{Air outlet (8)} \quad p = 1 \text{ atm} \quad (83)$$

$$\text{Symmetry (2, 3, 6, 7)} \quad u_{\perp} = 0 \quad (84)$$

Where the subscripts “ $\perp$ ” and “ $\parallel$ ” denote the vector components normal and parallel to the boundary, respectively.

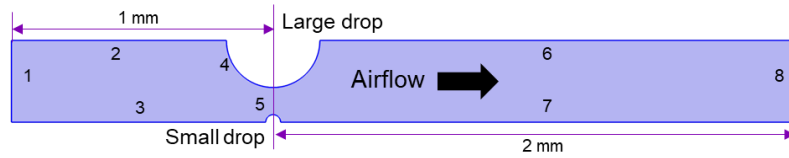


Figure 4.8. Numbered boundaries of the model domain

In addition, the problem of droplet motion is solved in a transient study, using the following boundary condition and initial condition as inputs.

$$\text{Walls (4, 5)} \quad \mathbf{v} = 0 \quad (85)$$

$$\text{Particle velocity (1, } t=0) \quad \mathbf{v} = \mathbf{u} \quad (86)$$

$$\text{No. of particles (1, } t=0) \quad N = 500 \quad (87)$$

$$\text{Droplet diameter} \quad d_{fog} = 16 \mu\text{m} \quad (88)$$

Here, 500 droplets provide sufficient samples to represent the fog droplets going through the collection process, allowing a rather accurate prediction of motion and capture of droplets. In addition, the particle diameter of  $16 \mu\text{m}$  is selected according to the mean diameter of fog droplets from the experiment.

### 4.3.3 Numerical method

The solution to the preceding system of equations is approximated through a Finite Element Method in COMSOL Multiphysics software, using the available physical interfaces of (1) single phase laminar flow, and (2) particle tracing. The fluid properties are given in Chapter 3 and not repeated in this section. The variables used for simulation, i.e., the penetrating air velocity,  $u_p$ , the drop radius,  $r_1$  and  $r_2$ , and the drop spacing,  $l_w$ , are given in Section 4.4.4.

## 4.4 Results and discussion

### 4.4.1 Structure and morphology of micro-fiber grids

Figure 4.9a presents the optical microscope image of a PVDF-HFP micro-fiber grid with 0.3 mm fiber spacing and 10  $\mu\text{m}$  fiber diameter. Overall, the microfibers exhibit a uniform size and an intact appearance. The fibers are aligned orthogonally, forming an ordered pattern of square grids. Moreover, Figure 4.9b provides a closer look at the crossing point between two perpendicular fibers in the grid. At the crossing points, the fibers are joined together, forming a solid connection. The joining process occurs during the NFES fabrication process. The fibers produced by NFES are not completely dry upon deposition, thus the upper fiber can adhere to the lower fiber at the crossing point. Subsequently, the joint solidifies as the fibers cure, resulting in a cohesive fiber connection. The solid joint helps maintain the stability and integrity of the micro-fiber grid, as well as preventing individual fibers from shifting or separating.

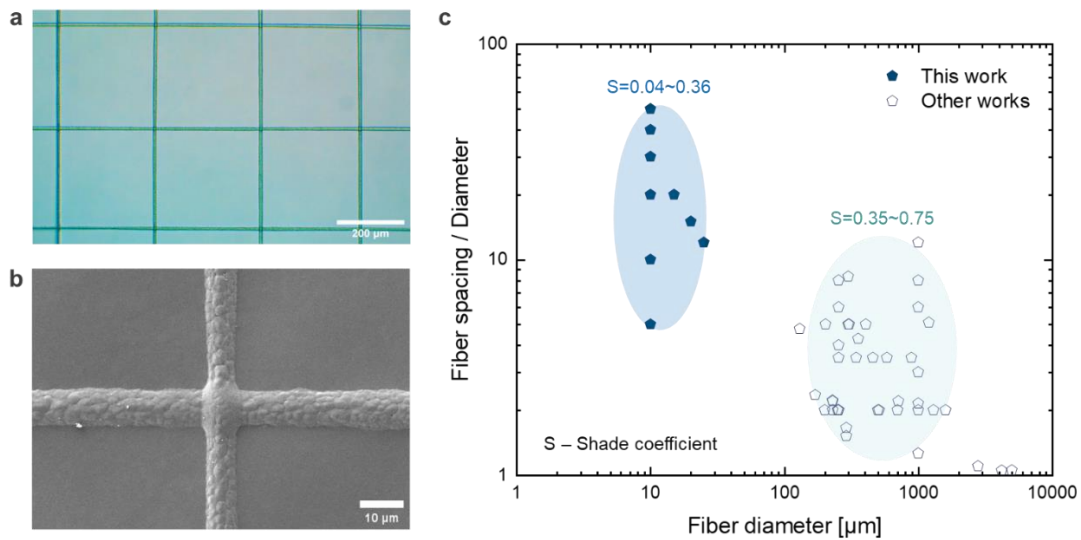


Figure 4.9. Microfiber grid with thin fiber diameter and wide fiber spacing. (a) Optical microscopic image of micro-fiber grids with 0.3 mm fiber spacing and 10  $\mu\text{m}$  fiber diameter. (b) Scanning electron microscope (SEM) images of crossing point between two perpendicular fibers. (c) Comparison of fiber diameter, spacing, and shade

coefficient of the micro-fiber grid in this study with other reported fog collectors based on permeable grids [12, 20, 29, 33, 56, 59, 70, 80, 154, 162-165, 181, 186-190].

The preceding morphology results in micro-fiber grids that have small fiber diameter and wide fiber spacing, leading to a low ratio of solid coverage. Figure 4.9c shows the comparison of fiber grids in this work with other fiber-based fog collectors in terms of the fiber diameter and the ratio of fiber spacing to diameter. The micro-fiber grids show exceedingly small diameters of 10 ~ 25  $\mu\text{m}$  and relatively large ratios of fiber spacing to diameter of 5 ~ 50. In contrast, the fiber diameter and spacing-to-diameter ratio used in other studies are in the range of 200~5000  $\mu\text{m}$  and 2~12, respectively [12, 20, 80]. As a result, the solid coverage ratio of the micro-fiber grid is comparably low, which is described using shade coefficient, calculated as the area of obstacles (fibers),  $A_b$ , divided by the grid area of collector,  $A_c$ , as shown in Eq. (89).

$$SC = \frac{A_b}{A_c} = \frac{2l_{sp}/d_{fiber} - 1}{(l_{sp}/d_{fiber})^2} \quad (89)$$

where  $l_{sp}$  is the fiber spacing, and  $d_{fiber}$  is the fiber diameter. The optimal shade coefficient for a fog collector based on thick fibers is in the range of 0.5-0.6 [21]. In contrast, the shade coefficient for micro-fiber grids in this study ranges from 0.04 to 0.36, which is generally smaller than the optimal value, as well as other reported shade coefficient referenced in the figure. The differences in fiber diameter, spacing and shade coefficient allow investigating the droplet capture on micro-fiber grids, which is seldom discussed in previous research.

#### 4.4.2 Waterdrop clogging on micro-fiber grids

The microfiber grid is placed in a fog flow of 180 g h<sup>-1</sup> for 1 hour to observe the formation of waterdrops with a polydisperse size distribution. Figure 4.10a depicts the waterdrops on micro-fiber grids with 0.5 mm spacing. The waterdrops maintain a nearly spherical shape because of surface tension, and their diameter varies from slightly larger than fiber to millimeter scale. The number fraction of waterdrops of different diameters follows an exponential distribution (see Figure 4.10b). Moreover, the grids with spacing of 0.1, 0.3 and 0.5 mm and fiber diameter of 10, 15, and 25  $\mu\text{m}$  follow the same distribution curve, suggesting that the distribution of waterdrop size is independent of the fiber spacing and diameter in the tested range.

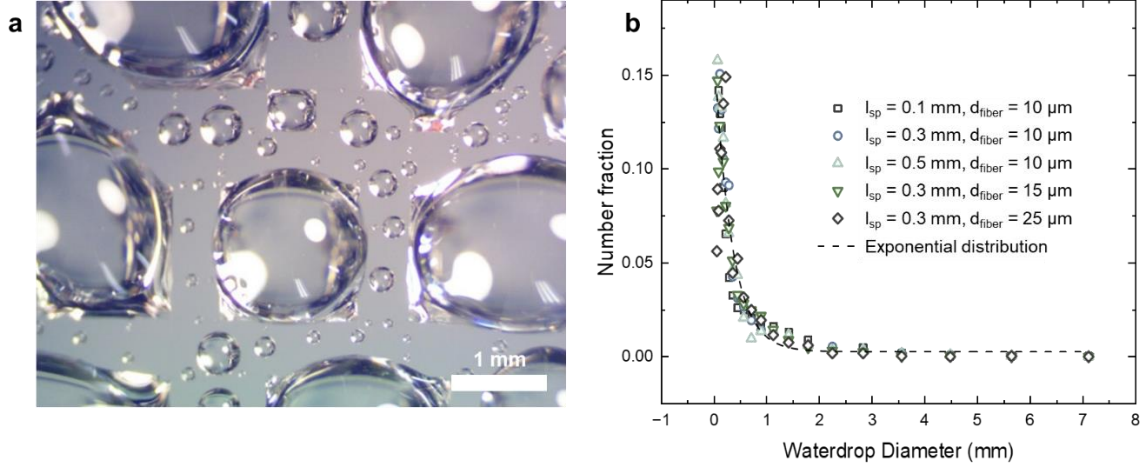


Figure 4.10. Clogging of micro-fiber grids due to the formation of waterdrops with polydisperse size distribution and spaced dispersion. (a) Optical microscope image of waterdrops adhering to a micro-fiber grid with 0.5 mm fiber spacing and 10  $\mu$ m fiber diameter. (b) Number fractions of waterdrops with different diameters on fiber grids with 0.1, 0.3 and 0.5 mm fiber spacing and 10, 15, 25  $\mu$ m fiber diameter. The number fractions are obtained by the logarithmic binning of the measured waterdrop diameters.

In addition, the waterdrops are dispersed on the micro-fiber grid at certain spacing. As shown in Figure 4.11a, the spacing between neighbor waterdrops follows a normal distribution, spanning from zero to 0.3 mm for grids with 0.1, 0.3 and 0.5 mm spacing. The increasing fiber spacing from 0.1 to 0.5 mm leads to larger waterdrop spacing with a broader distribution, indicating the spacing between waterdrops increases with the fiber spacing. As a result, the mean waterdrop spacing  $l_w$  correlates with the fiber spacing  $l_{sp}$  (see the insets of Figure 4.11a), following a power-law curve represented by Eq. (90), considering  $l_w = 0$  when fiber spacing is zero and  $l_w = \infty$  when fiber spacing approaches infinity.

$$l_w = 0.22l_{sp}^{0.63} \quad (90)$$

where  $l_w$  and  $l_{sp}$  take the unit of millimeter. In addition, the distribution of waterdrop spacing is independent of fiber diameter of 10~25  $\mu$ m (see Figure 4.11b). Therefore, the spaced dispersion of waterdrops on micro-fiber grids is mainly related to the fiber spacing rather than the fiber diameter.

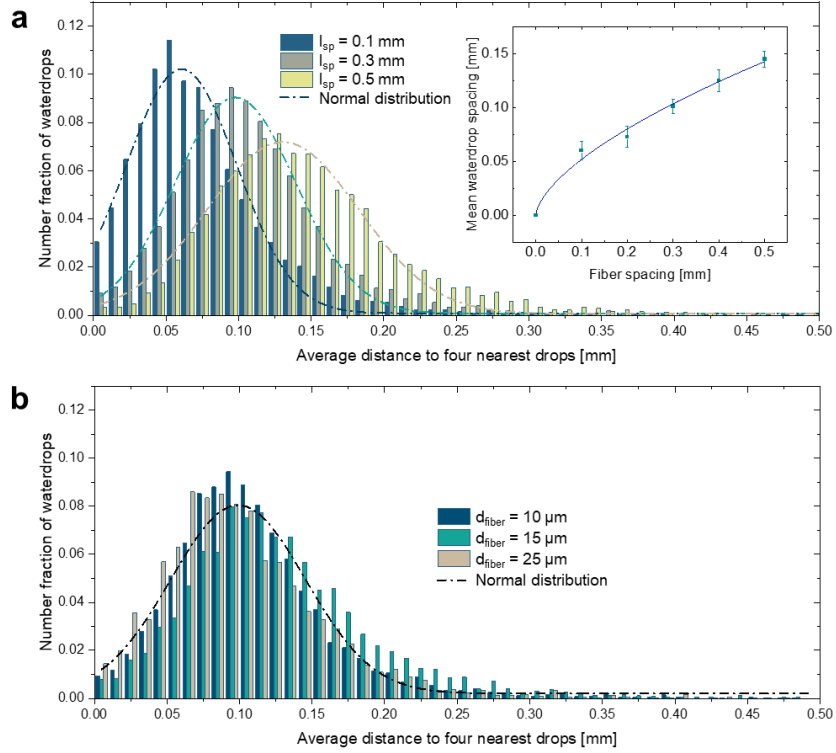


Figure 4.11. Number fraction of waterdrops with different distance to neighbor drops on fiber grids with (a) 0.1, 0.3 and 0.5 mm fiber spacing, and (b) 10, 15 and 25  $\mu m$  fiber diameter. The inset of (a) shows the correlation between the fiber spacing and mean waterdrop spacing.

Interestingly, the dispersion of waterdrops exhibits a specific pattern, where large waterdrops are far from each other, and the small waterdrops satellite around the large drops to fill the gaps. As illustrated by Figure 4.12a, the pattern is formed through the coalescence of waterdrops. Specifically, the volume of the larger drop is the sum of four smaller drops, but the coverage area of the larger drop is smaller than all smaller drops combined, due to maintaining a spherical shape. Consequently, coalescence refreshes the bare surface on the microfibers, where a new round of capture and growth takes place, forming small waterdrops that satellites around the large drop.

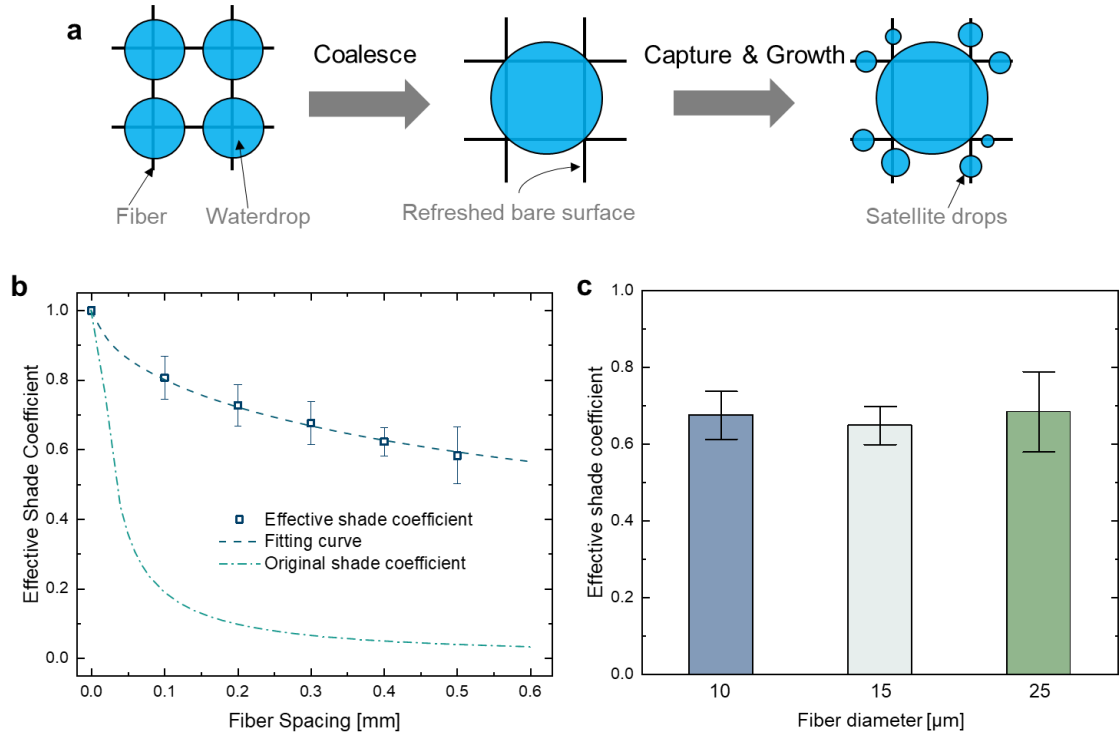


Figure 4.12. Waterdrop clogging pattern and increased effective shade coefficient. (a) Schematic of waterdrop pattern formed by the coalescence of waterdrops. (b) Effective shade coefficient and original shade coefficient at fiber spacings of 0.1, 0.2, 0.3, 0.4, and 0.5 mm. (c) Effective shade coefficient at fiber diameter of 10, 15, and 25 μm.

The growth of waterdrops clogs the micro-fiber grids by obstructing the grid openings. The effective shade coefficient of clogged grids is used to represent the water clogging [21, 162], as calculated in Eq. (91) using the projected area of fiber and waterdrops.

$$SC_w = \frac{A_w + A_b}{A_c} \quad (91)$$

The effective shade coefficient is the average of the 1-hour test results. As illustrated in Figure 4.12b, the effective shade coefficient ranges from 0.58 to 0.81, which is 4.5 ~ 14 times larger than the original shade coefficient of the bare micro-fiber grids. The drastically increased effective shade coefficient implies that the major area of micro-fiber grid is clogged by waterdrops. In addition, the effective shade coefficient decreases as the fiber spacing increases from 0.1 mm to 0.5 mm, suggesting that the grid with small spacing is more easily clogged by waterdrops. Moreover, the effective shade coefficient remains constant for fiber grids with diameters of 10, 15 and 25 μm at a fixed spacing of 0.3 mm (see Figure 4.12c), indicating a negligible effect of fiber diameter on waterdrop clogging in the tested range. The effective shade coefficient is fitted to a curve by considering  $SC_w = 1$  when fiber spacing  $l_{sp}$  is zero and  $SC_w = 0$  when  $l_{sp}$  approaches infinity, which is in the form of Eq. (92).

$$SC_w = \frac{1}{1 + 1.063l_{sp}^{0.63}} \quad (92)$$

where  $l_{sp}$  takes the value at the unit of millimeter. Compared to the bare grids with small original shade coefficient, the enlarged effective shade coefficient due to clogging may enhance droplet capture by providing a larger projected area, which requires further verification from experiments.

It is worth noting that both the waterdrop spacing and effective shade coefficient are correlated to the 0.63 power of fiber spacing  $l_{sp}$ , suggesting the effective shade coefficient and the mean waterdrop spacing are inversely proportional. The first-order inverse relationship hints the feasibility of approximating the 3D waterdrop array into a 2D model, which is proven useful in Section 4.4.4.

#### 4.4.3 Waterdrop-assisted capture of fog droplets

To verify the effectiveness of waterdrop on capturing fog droplets, this study compares the time evolvement of effective shade coefficient and waterdrop volume on two fiber grids with the same original shade coefficient. Figure 4.13a illustrates the effective shade coefficient of two grids MF1 ( $d_{\text{fiber}} = 10 \mu\text{m}$ ,  $l_{sp} = 0.1 \text{ mm}$ ) and MF2 ( $d_{\text{fiber}} = 100 \mu\text{m}$ ,  $l_{sp} = 1 \text{ mm}$ ) exposed to a fog flow of  $55 \text{ g h}^{-1}$  at an airflow velocity of  $u_0 = 0.45 \text{ m s}^{-1}$  from 0 to 30 seconds. The duration of 0~30 seconds is selected to focus on the initial growth of waterdrops, which is not affected by waterdrop shedding. The two grids have the same original shade coefficient of 0.19; their effective shade coefficient increases with distinct rates, following an exponential decay function. Specifically, the effective shade coefficient of MF1 reaches 0.72 at 30 s, which is two times higher compared to MF2 with an effective coefficient of 0.36 at 30 s. The result directly indicates that the MF1 is more easily clogged by waterdrops, as the two grids start with the same original shade coefficient. The difference in clogging results from that the opening of MF1 is obstructed earlier by small waterdrops than MF2. This is evidenced by Figure 4.13c, which displays that the opening of MF1 is quickly clogged by small waterdrops in 30 seconds, while MF2 remains unclogged with large open areas.

Figure 4.13b depicts the variation of waterdrop volume per grid area on MF1 and MF2 during the test. The waterdrop volume on MF1 increases linearly with a rate of  $0.162 \mu\text{L mm}^{-2} \text{ min}^{-1}$ , which is 48% faster than MF2 with a rate of  $0.109 \mu\text{L mm}^{-2} \text{ min}^{-1}$ , indicating that MF1 captures fog droplets more effectively than MF2. It is reasonable to speculate that the enhanced capture of fog droplets on MF1 results from the waterdrop clogging instead of bare fibers based

on the following reasons. First, Figure 4.13c shows that the small waterdrops quickly cover the fiber surface in 5 seconds. Therefore, the obstacles that interact with incoming fog droplets are mostly waterdrops instead of fibers. Second, the increased effective shade coefficient leads to a larger impermeable area that can interact with the fog droplets, which affects the fog capture according to Rivera's theoretical model [21].

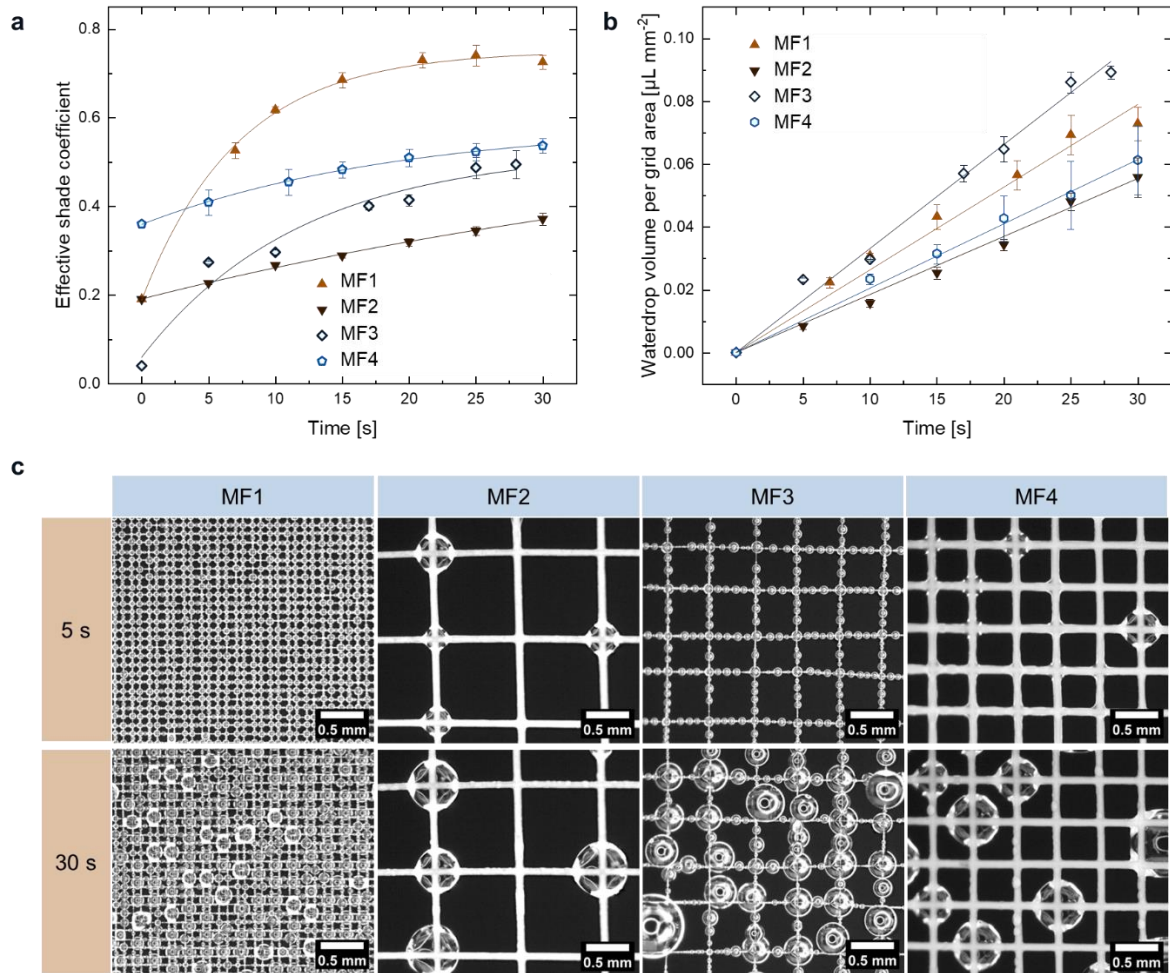


Figure 4.13. Enhanced growth of waterdrops on micro-fiber grids MF1 and MF3 compared to thick-fiber grids MF2 and MF4. Time evolution (0 ~30 s) of (a) effective shade coefficient and (b) waterdrop volume per grid area for the grids placed in the fog flow of  $55 \text{ g h}^{-1}$  liquid flow rate and  $0.45 \text{ m s}^{-1}$  velocity. (c) Optical microscope images of waterdrops adhering to fiber grids MF1-4 at 5 seconds and 30 seconds.

However, the preceding grid MF1 has both thinner fiber diameter and smaller spacing compared to MF2. To confirm whether the enhancement due to waterdrop clogging is based on small fiber diameter or narrow spacing, grids with the same spacing and different diameters are compared at the same condition of fog flow. Figure 4.13c displays waterdrop growth on two grids with the same fiber spacing of 0.5 mm and different fiber diameters of  $10 \mu\text{m}$  (MF3) and  $100 \mu\text{m}$  (MF4). At 30 seconds, more waterdrops of larger sizes are attached to MF3 compared to MF4. Moreover, Figure 4.13a-b shows the effective shade coefficient and the

waterdrop volume of the two grids. Overall, both effective shade coefficients of the two grids approach 0.5 at 30 seconds, representing a similar degree of clogging by waterdrops. In contrast, the waterdrop volume on MF3 increases with a rate of  $0.2 \mu\text{L mm}^{-2} \text{min}^{-1}$ , which is 60% faster than MF4 with a rate of  $0.124 \mu\text{L mm}^{-2} \text{min}^{-1}$ . The result indicates that the waterdrops on micro-fiber grids capture fog droplets more effectively than thick fiber grids when they are similarly clogged.

This study introduces the “visibility” of waterdrops to explain the enhanced capture on the clogged micro-fiber grids. Overall, a waterdrop is “visible” when its geometry affects the capture of fog droplets. As shown in Figure 4.14a, a small waterdrops formed on a microfiber with a diameter  $d_{f1}$  and a thick fiber with a diameter  $d_{f2}$ . When the waterdrop grows to a diameter greater than the diameter of the microfiber  $d_{f1}$ , it becomes “visible” to the airflow and captures the fog droplets differently compared to the bare fiber. On one hand, the diameter of waterdrop is larger than the microfiber, providing a greater area as an obstacle to capture fog droplets. On the other hand, the waterdrop-laden fiber affects the Stokes number of fog droplets, as shown in Eq. (93) [6].

$$Stk = \frac{\rho_w d_{fog}^2 u_p}{18\mu d} \quad (93)$$

where  $\rho_w$  and  $d_{fog}$  are the density and diameter of the fog droplet, respectively,  $\mu$  is the viscosity of air,  $d$  is the characteristic length of the obstacle, and  $u_p$  is the velocity of air that penetrates the grid. Compared to bare fibers using  $0.5d_{f1}$ , the characteristic length of the waterdrop-laden fiber increases to waterdrop radius  $r_c$  [24], which reduces the Stokes number and the ratio of captured fog droplets. In contrast, a thick fiber with a diameter  $d_{f2} > 2r_c$  makes the small waterdrops “invisible” to the airflow, because the characteristic length of the Stokes number and the area to capture fog droplets are determined by the thick fiber instead of the waterdrop. The “visibility” of waterdrops is evidenced by Figure 4.14b, which compares the waterdrop growth on fibers with different diameters. On the  $25 \mu\text{m}$  fiber, waterdrops are always exposed to airflow regardless of waterdrop size. Conversely, thick fibers with diameter of 100 and  $150 \mu\text{m}$  tend to shade the waterdrops until the drops grow sufficiently large to be “visible”.

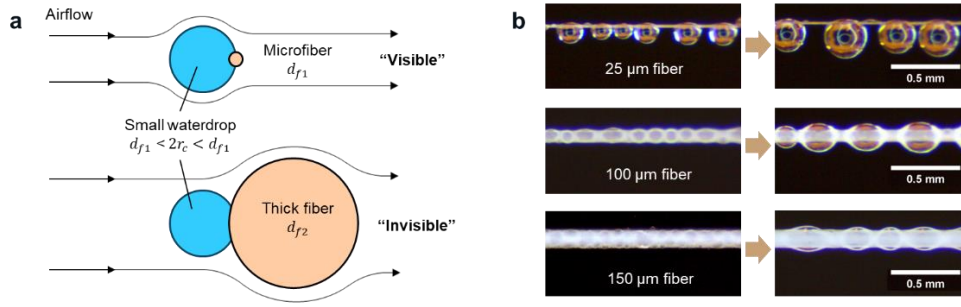


Figure 4.14. Waterdrop "visibility" to airflow and its effects on capturing fog droplets. (a) Schematic of visible and invisible waterdrops sitting on a microfiber and a thick fiber. (b) Microscopic image of waterdrops growing on fibers with diameters of 10, 100 and 150  $\mu\text{m}$ , evidencing the concept of "visible" waterdrops.

The effects of the "visible" waterdrops on droplet capture is evaluated using a model based on the study of droplet capture on wet fibers by Labbé et al. and the theory of droplet deposition by Langmuir [24, 43]. The model estimates the ratio of captured fog droplets  $\eta_b$  on the clogged grid using Eqs. (94) and (95).

$$\eta_b \propto \eta_{de} A_w \quad (94)$$

$$\eta_{de} = \begin{cases} 0 & (Stk < 0.125) \\ 0.466(\log_{10} 8Stk)^2 & (0.125 < Stk < 1.1) \\ Stk/(Stk + \pi/2) & (Stk > 1.1) \end{cases} \quad (95)$$

where  $\eta_{de}$  is the deposition efficiency, and  $A_w$  is the projected area of the waterdrop, which depends on the waterdrop radius as  $A_w \propto r_c^2$ . Taking the derivative of  $\eta_{de} A_w$ , a maximum  $\eta_b$  exists at a threshold waterdrop radius  $r_{th}$  as in Eq. (96).

$$r_{th} = \frac{4\rho_w d_{fog}^2 u_p}{9e\mu} \quad (96)$$

where  $e$  is the Euler' number.

The modeled threshold radius identifies whether a growing waterdrop positively or negatively affects the droplet capture. Figure 4.15a illustrates the modeled threshold radius through the variation of  $\eta_{de}$ ,  $A_w$  and  $\eta_b$  against the waterdrop radius  $r_c$  at a penetrating velocity  $u_p = 0.1 \text{ m s}^{-1}$ . A threshold radius  $r_{th} \sim 230 \mu\text{m}$  exists as a result of the monotonically increasing  $A_w$  (normalized by dividing  $1 \text{ mm}^2$ ) and the monotonically decreasing  $\eta_{de}$ . For waterdrops smaller than the threshold, the growth of waterdrop provides a larger projected area to capture fog droplets, resulting in an increasing ratio of captured fog droplets  $\eta_b$  as the waterdrop grows. In contrast, waterdrops larger than the threshold gradually loses their enhancement, because the fog droplets tend to pass around the waterdrops due to the reduced Stokes number. The

effect of threshold radius is experimentally evidenced by the growth rate of waterdrops on a single fiber (see Figure 4.15b). The growth rate gradually increases as the waterdrops volume grows from 0 to  $2.7 \mu\text{L cm}^{-1}$  as an exponential function, which implies that the increase in waterdrops size enhances fog capture. After 150 seconds, the growth rate slowly decreases, indicating that the Stokes number plays a dominant role and negatively affects the fog capture.

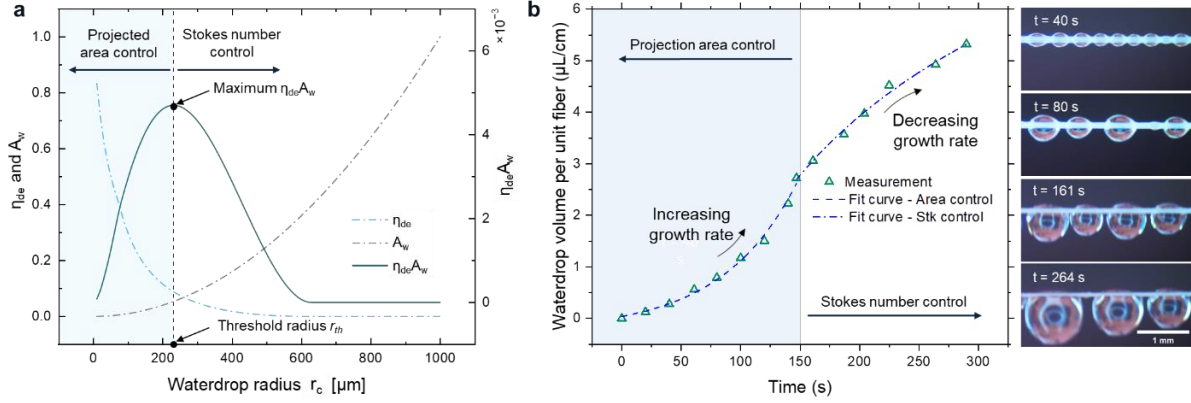


Figure 4.15. Competing effect of projected area and Stokes number on droplet capture. (a) Plot of modeled  $\eta_{de}$ ,  $A_w$  and  $\eta_{de} A_w$  as functions of  $r_c$  at  $u_p = 0.1 \text{ m s}^{-1}$ . (b) Plot and image of waterdrop volume at different collection times.

Based on the “visibility” waterdrops, an obstacle size  $d$  can replace the waterdrop radius  $r_c$  or fiber diameter  $d_f$  as follows.

$$d = \begin{cases} 2r_c, & (d_f < r_c, \text{"visible"}) \\ d_f, & (d_f \geq r_c, \text{"invisible"}) \end{cases} \quad (97)$$

Therefore, the threshold radius  $r_{th}$  can be converted to a threshold obstacle size  $d_{th}$ , which is used to cast Eq. (96) into a dimensionless form  $\Phi_{th} = 8Re_d/(9e)$ , by defining a dimensionless obstacle size  $\Phi = d/d_{fog}$  and a droplet Reynolds number  $Re_d = \rho_w d_{fog} u_p / \mu$ . Depending on the threshold  $\Phi_{th}$ , the status of the waterdrop growth on fibers can be categorized into two phases (see Figure 4.16).

- For the thin fiber with an initial  $\Phi < \Phi_{th}$  in Phase I, the “visible” small waterdrops on the fiber enhance the fog capture by providing a larger area. After the waterdrop grows (dashed arrow line) to exceed the threshold  $\Phi_{th}$  and enters Phase II, the subsequent growth weakens the fog capture because of the decreasing Stokes number. In other words, the distance to the threshold line suggests a “positive” lifespan of waterdrops that enhance capture while continuously growing, otherwise the growth is “negative”.
- For the thick fiber starting with  $\Phi > \Phi_{th}$  in Phase II, the small waterdrops are initially “invisible” to the airflow because they are shaded by the thick fiber. When the

waterdrops grow larger than fiber and become “visible”, the increasing  $\Phi$  only weakens fog capture, suggesting a constant “negative” lifespan.

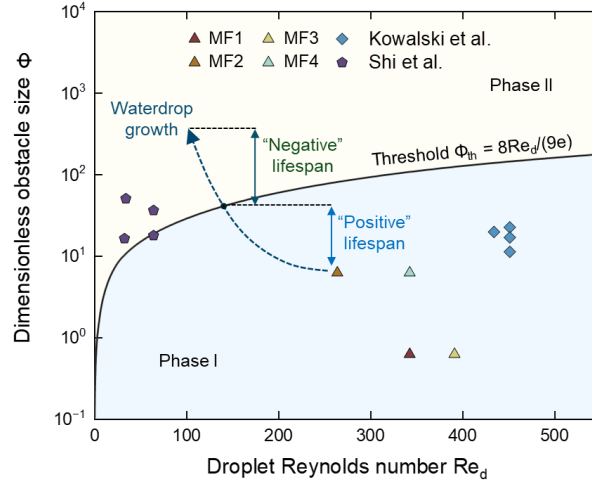


Figure 4.16. Phase diagram of the effect of “visible” waterdrops on fibers against the threshold dimensionless obstacle size  $\Phi$  and droplet Reynolds number  $Re_d$ .

The phase diagram is validated by the experiment of waterdrop growth. The points of 10  $\mu\text{m}$  fiber grids, MF1 and MF3, are further away from the threshold line compared to MF2 and MF4 with a diameter of 100  $\mu\text{m}$ , leaving a longer “positive” lifespan of waterdrop to enhance fog capture, which is consistent with the experiment result that waterdrop clogging on microfibers can enhance fog capture better than the thick fibers. The phase diagram is also validated using others work. For example, based on a similar fog flow of  $54 \text{ g h}^{-1}$ , the grid structures reported by Kowalski et al. are closer to the threshold line [80], indicating a shorter “positive” lifespan of waterdrop clogging. As a result, their water volume growth rate ranges from  $0.027 \sim 0.115 \mu\text{L mm}^{-2} \text{ min}^{-1}$ , which is lower than the micro-fiber grids with  $0.162 \sim 0.2 \mu\text{L mm}^{-2} \text{ min}^{-1}$ . On the other hand, the thick fiber diameter of the grid used by Shi et al. is in Phase II [20], suggesting that the waterdrop clogging is solely negative for droplet capture, which agrees with their findings that clog-relieving methods enhances the water collection on their grids. Overall, the micro-fiber grids have the most long-lived “positive” waterdrops, which explains the higher water growth rate of  $0.162$  and  $0.2 \mu\text{L mm}^{-2} \text{ min}^{-1}$  on MF1 and MF3, respectively.

#### 4.4.4 Effects of size difference and dispersion of waterdrops

The preceding section explains how waterdrops on micro-fiber grids affect the capture of fog droplets. However, in long-term fog harvesting, the waterdrops on the micro-fiber grid exist with a polydisperse size and a spaced dispersion, as introduced in Section 4.4.2. To understand

how size difference and dispersion of waterdrops affect fog capture, this study numerically simulates the fluid dynamics and droplet trajectory around waterdrop arrays.

The simulation requires the input of clogging drop radius  $r_1$ ,  $r_2$  and  $l_w$  as introduced in Section 4.3, which can be obtained using the experimental measurements of  $l_w$  and  $SC_w$  as follows. First, the effective shade coefficient  $SC_w$  can be expressed in Eq. (98) by neglecting the area contribution of fibers, which is a reasonable simplification considering most fibers are covered by waterdrops.

$$SC_w = \frac{r_1 + r_2}{r_1 + r_2 + l_w} = \frac{1}{1 + l_w/(r_1 + r_2)} \quad (98)$$

Then,  $r_1 + r_2$  can be calculated using the empirical correlations of the effective shade coefficient  $SC_w = 1/(1+1.063l_w^{0.63})$  and the waterdrop spacing  $l_w = 0.22l_{sp}^{0.63}$  from Eqs. (90) and (92). As a result,  $r_1 + r_2$  is calculated as a constant of 0.207 mm. This is consistent with the conclusion in Section 4.4.2 that the distribution of droplet size is independent of the fiber spacing and diameter in the tested range. To better represent the size difference between waterdrops, a parameter of relative difference,  $c$ , is defined in Eq. (99).

$$c = \frac{r_1 - r_2}{r_1 + r_2} = \frac{2r_1 - 0.207mm}{0.207mm} \quad (99)$$

With Eq. (99), this study considers  $0 < c < 1$  to simulate the effects of size differences. In addition,  $l_w$  is obtained using  $l_w = 0.22l_{sp}^{0.63}$  to simulate the effects of spaced dispersion, where  $l_{sp}$  varies from 0.1 – 1 mm to cover the spacing of micro-fiber grid used in the experimental study.

Simulation shows that the airflow is deflected towards the small waterdrop because of the size difference between the waterdrops. Figure 4.17 depicts the streamline of the airflow penetrating the grid at a velocity of  $u_p = 0.1 \text{ m s}^{-1}$ , in which two waterdrops with a relative difference of 0.73 are placed on a fiber grid with 0.3 mm spacing. The direction of streamlines from the inlet boundary is severely deflected by the large waterdrop towards the small waterdrop because of the fluid continuity. As a result, the deflection of airflow increases the local velocity in the vicinity of the small waterdrop to  $\sim 0.4 \text{ m s}^{-1}$ . The result is consistent with the results of Lee et al.'s experiments based on particle-image velocimetry [59], in which large waterdrops severely distort the airflow field.

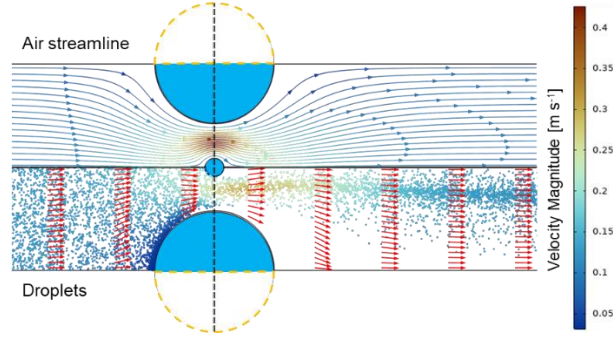


Figure 4.17. The visualized simulation results for air streamline (top) and droplet trajectory (bottom) calculated using the model with  $c = 0.73$  and  $l_{sp} = 0.3$  mm.

To evaluate the effect of the size difference on airflow deflection, the mean velocity is taken along the symmetrical axis of the large and small waterdrop as  $u_l$  and  $u_s$ . As shown in Figure 4.18a, for  $u_p = 0.1$ - $0.5$  m s<sup>-1</sup>, increasing the relative difference  $c$  from 0 to 1 monotonically increases the ratio  $u_s/u_l$  from 1 to 1.8~2.0, depending on the magnitude of  $u_p$ . The increasing ratio  $u_s/u_l$  with the relative difference  $c$  indicates a gradual deflected airflow towards the small drop. The result suggests that the increasing size difference between neighboring waterdrops leads to a more deflected airflow towards the small waterdrop.

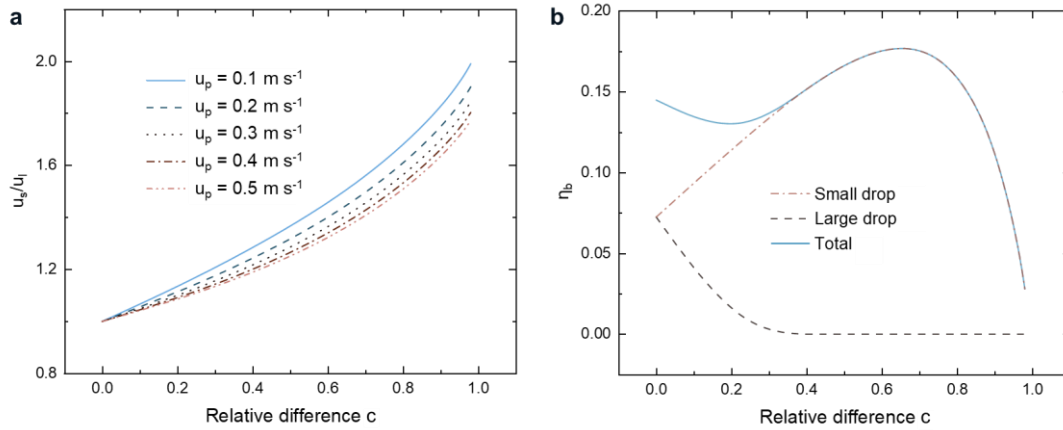


Figure 4.18. Size difference effect on airflow deflection and droplet capture. (a) Plot of the ratio between  $u_s$  and  $u_l$  as functions of  $c$  at the penetrating velocity of  $u_p = 0.1 - 0.5$  m s<sup>-1</sup>. (b) Plot of the ratio of captured droplets  $\eta_b$  as functions of  $l_{sp}$  at the penetrating air velocity of  $u_p = 0.1$  m s<sup>-1</sup>.

The airflow deflection due to the size difference further affects droplet capture. As shown in Figure 4.17, the trajectories of challenge droplets are also deflected towards the small waterdrop following the streamline of airflow, leading to more droplets interacting with the small waterdrop. In contrast, the challenge droplets slowly pass around the large drop without deposition, as if they accumulate on the surface of the large drop. In addition, the variation of local velocity and waterdrop size further affects the local Stokes number [199], which governs droplet capture. Consequently, the ratio of captured challenge droplets varies with relative

difference  $c$ . As depicted in Figure 4.18b, increasing  $c$  monotonically reduces  $\eta_b$  on the large waterdrop. When  $c$  exceeds 0.3, the large waterdrop allows most challenge droplets to follow the air streamline without impacting the drop, reducing  $\eta_b$  to zero. For the small waterdrop, both the increased local airflow velocity and the reduced waterdrop radius enhance the capture of droplets, reaching a peak ratio of  $\eta_b = 18\%$  at  $c = 0.7$ . However, the ratio  $\eta_b$  on small waterdrop reduces as  $c$  continues to increase, because the area to capture challenge droplets reduces with increasing  $c$ . As a result, the total ratio of captured droplets is enhanced for  $c$  of 0.4-0.75, and rapidly reduced as  $c$  further approaches 1. Overall, the polydisperse size of waterdrops leads to a specific pattern of droplet capture: the large waterdrop deflect the airflow to the satellite small drops, where the droplets are effectively captured.

In addition, the spaced dispersion of waterdrops, which is represented by the waterdrop spacing  $l_w$  as a function of fiber spacing  $l_{sp}$ , also affects droplet capture. As depicted in Figure 4.19a, at a velocity of  $u_p = 0.1 \text{ m s}^{-1}$  and a relative difference of  $c = 0.7$ ,  $u_s/u_l$  reduces from 1.65 to 1.5 as the fiber spacing increases from 0.1 mm to 1 mm, indicating a weakened deflection of airflow towards the small drop. The weakened deflection results from the opening provided by the large fiber spacing, allowing the airflow to pass through the grid without interacting with waterdrops. Consequently, the ratio of captured droplets  $\eta_b$  monotonically decreases from 0.4 to 0.07 with the increasing fiber spacing, indicating that smaller spacing is more capable to capture droplets at a fixed  $u_p$  and  $c$ .

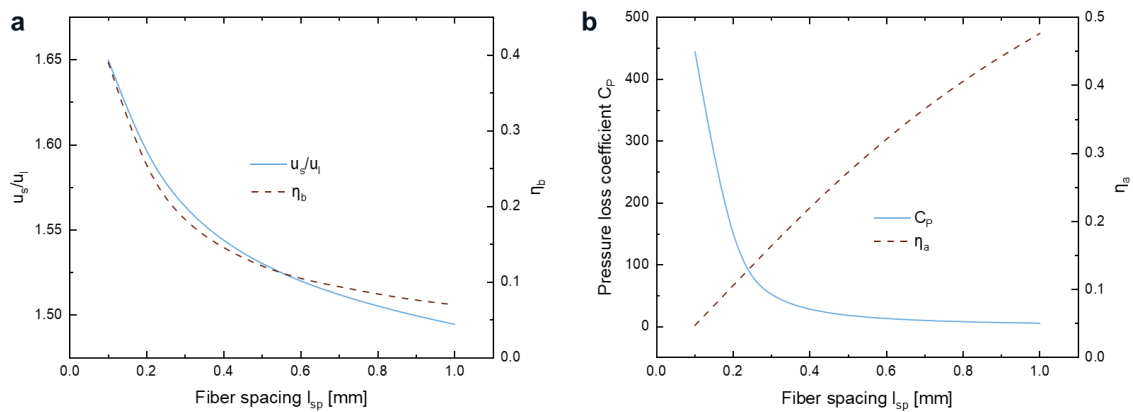


Figure 4.19. Drop dispersion effect on airflow deflection and droplet capture. (a) Plot of the ratio between  $u_s$  and  $u_l$  and the ratio of captured droplets  $\eta_b$  as functions of  $l_{sp}$  at  $u_p = 0.1 \text{ m s}^{-1}$ . (b) Plot of the pressure loss coefficient  $C_p$  and the ratio of penetrating airflow  $\eta_a$  as functions of  $l_{sp}$  at  $u_p = 0.1 \text{ m s}^{-1}$ .

On the other hand, the dispersion of waterdrops also affects the pressure loss of the collector to further impact droplet capture. Figure 4.19b illustrates the pressure loss coefficient  $C_p$  on the grid and ratio of penetrating airflow  $\eta_a$ . Increasing fiber spacing from 0.1 mm to 1

mm reduces  $C_p$  from 450 to 5.3, because the small fiber spacing leads to less areas clogged by waterdrop, reducing the pressure loss generated by airflow. Using the correlation  $\eta_a = 1.43(C_p+1.85)^{-0.56}$  obtained in Chapter 3, the reduced pressure loss increases the value of  $\eta_a$  from 5% to 50%, allowing more airflow to penetrate the fiber grid. Overall, the waterdrop dispersion has opposite effects on  $\eta_a$  and  $\eta_b$ , enabling optimizing the overall collection efficiency by controlling the fiber spacing.

#### 4.4.5 Micro-fiber grid fog collector

The fog collectors are assembled based on micro-fiber grids with different morphology and patterns, displaying an ultra-light feature. Figure 4.20a shows the micro-fiber grids fabricated with NFES, including (1) a square grid with 0.1 mm spacing and 10  $\mu\text{m}$  diameter, (2) a square grid with 0.3 mm spacing and 25  $\mu\text{m}$  diameter, and (3) a rectangular grid with 0.6 mm mesh length, 0.15 mm mesh width and 10  $\mu\text{m}$  diameter. The fabricated grids are light weighted due to minimal material usage. For example, a grid area of 60 mm  $\times$  60 mm with 0.1 mm spacing and 10  $\mu\text{m}$  fiber diameter weighs only 1.8 mg.

The fabricated grids maintain a stable structure and a transparent appearance after the assembly of the fog collector. As shown in Figure 4.20b, a fiber grid with 0.3 mm fiber spacing and 10  $\mu\text{m}$  fiber diameter is orderly secured between two copper gaskets. The integrity of the structure results from the solid jointing between perpendicular fibers. The fiber in the fog collector is sparsely arranged with a comparable diameter to natural spider silk (*see* left inset of Figure 4.20b), allowing the transmission of optical lights. This feature is also observed for the microfiber collectors with a narrower spacing, as shown in right inset of Figure 4.20b, where the characters of “WATERLOO” is clearly visible when placed below a collector with 0.1 mm fiber spacing and 10  $\mu\text{m}$  fiber diameter.

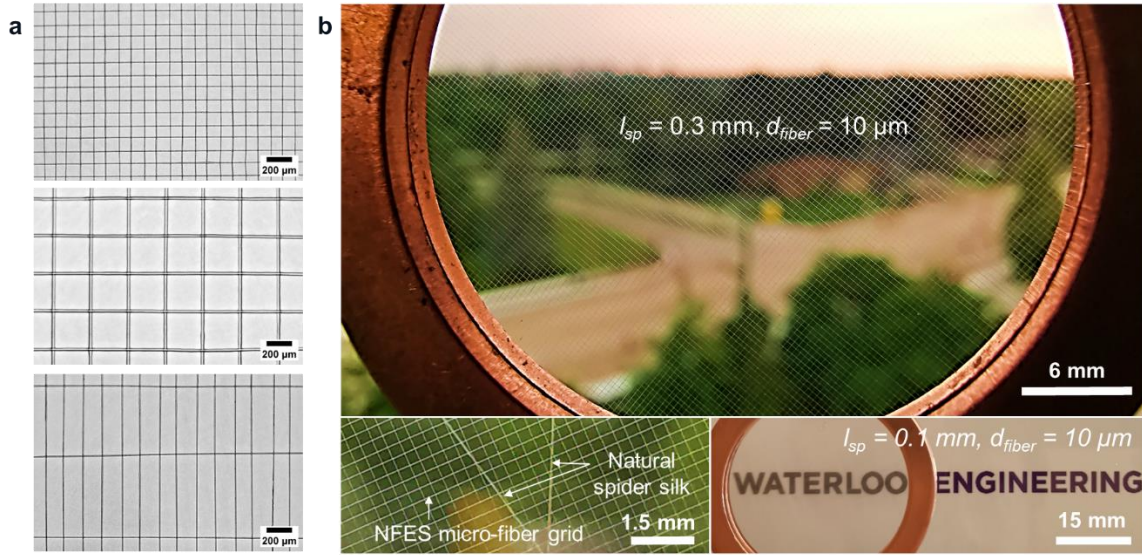


Figure 4.20. Fog collectors assembled using micro-fiber grid. (a) Optical microscope image of micro-fiber grids with tunable fiber diameter, spacing and mesh aspect ratio. (b) Digital image of an assembled fog collector fixing a micro-fiber grid between two copper gaskets. The left inset image compares the micro-fiber grid to natural spider silks. The right inset image shows the visible characters “WATERLOO” when placed below a fog collector with 0.1 mm fiber spacing and 10 μm fiber diameter.

The collected water over time on the fog collectors is measured in a fog flow of  $180 \text{ g h}^{-1}$  at a velocity of  $0.45 \text{ m s}^{-1}$ . The measurement indicates that the water collection rate of the micro-fiber fog collectors depends on fiber spacing. Figure 4.21a displays the collected water amount per collector area for square grids with a fixed fiber diameter of 10 μm and a varying spacing from 0.05-0.5 mm. The collected water for all grids increases linearly with times, which indicates a rather stable water collection rate throughout the 1 hour period of the test. Among the tested collectors, the grids with 0.2~0.5 mm spacing have higher collection rate of fog water, which peaks at 0.3 mm spacing with a rate of  $3.66 \text{ ml cm}^{-2} \text{ h}^{-1}$ . In contrast, the grids with 0.05 mm spacing have the lowest collection rate of  $2.23 \text{ ml cm}^{-2} \text{ h}^{-1}$ . The dependance on fiber spacing is the result of the opposite effect of waterdrop dispersion on  $\eta_a$  and  $\eta_b$ , where 0.3 mm spacing optimizes the collection efficiency.

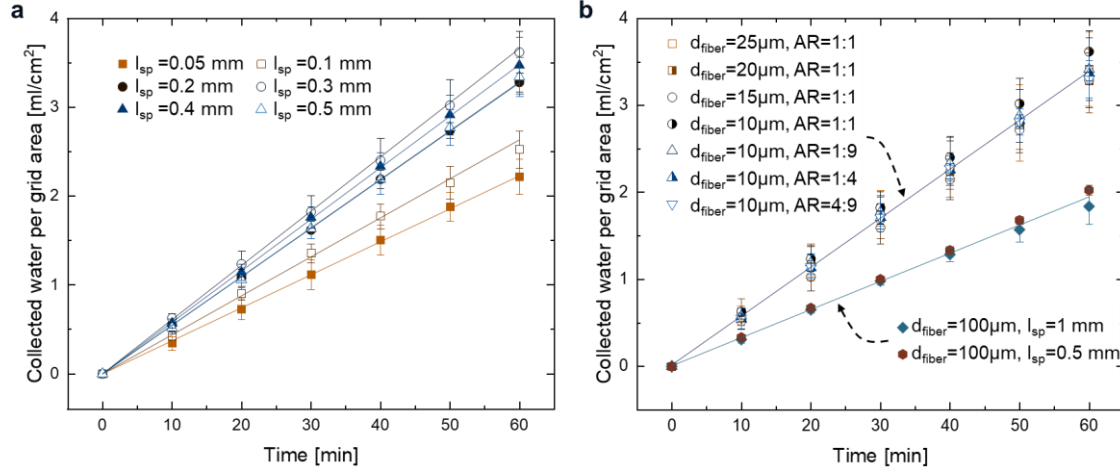


Figure 4.21. Collected water per grid area over time for collectors with (a) fiber spacings of 0.05-0.5 mm, and (b) fiber diameters of 10-25  $\mu m$  and mesh aspect ratio of 1:1, 4:9, 1:4 and 1:9.

In addition, the variation of fiber diameter and grid aspect ratio shows negligible effect on water collection rate. Figure 4.21b shows the amount of collected water over time for the collectors with a fiber diameter of 10~25  $\mu m$  and a grid aspect ratio of 1:1~1:9; the collectors have the same area of 0.09 mm<sup>2</sup> for each single mesh, which is equivalent to 0.3 mm spacing square grids. Overall, the data points show a similar trend and collapse onto the same fitting line. A one-way ANOVA test with a significance level of 0.05 also yields a small F value of 0.103, indicating that the amount of collected water is not significantly different between different grids [200]. The independence of collection rate on fiber diameter results from the small diameter compared to the threshold. Specifically, for fiber grids with diameter of 10~25  $\mu m$ , the positive lifespan of “visible” waterdrops that enhance capture are quite similar, considering the threshold waterdrop radius is in the order of several hundreds of micrometers. In addition, the change in aspect ratio hardly affects the area of fiber to which waterdrops can attach, since the area of the single mesh is constant. As a result, the waterdrop size and dispersion are unaffected by mesh aspect ratio, resulting in the independence of collection rate.

Figure 4.21b also shows the water collection over time on thick fiber grids with diameter of 100  $\mu m$  and fiber spacing of 0.5 mm and 1 mm. The water collection rate on the two thick-fiber grids is almost the same as 1.94 ml cm<sup>-2</sup> h<sup>-1</sup>, which is ~47% slower than the peak collection rate of 3.66 ml cm<sup>-2</sup> h<sup>-1</sup> obtained on the 0.3 mm spacing grid, and 13% slower than the slowest rate on microfiber grids of 0.05 mm spacing. Therefore, the micro-fiber grids are generally more effective compared to the thick-fiber grids.

The fast water collection on the micro-fiber grids leads to high water collection efficiency. Figure 4.22a shows the water collection efficiency with fiber spacings of 0.1~0.5 mm and a

diameter of 10  $\mu\text{m}$ . The grids with 0.3 mm spacing show the highest efficiency of 21.4%, while the 0.05 mm spacing leads to the lowest collection efficiency of 13.1%. Also, the 0.2~0.5 mm spacing grids exhibit similar collection efficiencies, which are generally larger than 19% with overlapping error bars. Figure 4.22b compares the experimental collection efficiency of this study with other fog collectors based on the obstacle size. Generally, this study shows the highest efficiency compared to other permeable fiber grids, such as wire mesh [62], Raschel mesh [62], and fog harp [20, 80]. Additionally, this study is among the most effective fog collectors compared to other structures, such as the pyramid kirigami [181], cactus kirigami [29], and 3D SHBL frame [70]. Notably, 3D SHBL frame has a high efficiency of 25%, which may result from the large volume of the fabricated 3D structure, because the fog flow is intercepted multiple times when penetrating the collector. Similarly, planar structures such as micro-fiber grids or fog harps can also benefit from 3D structuring if stacked as a multilayer collector [19, 157].

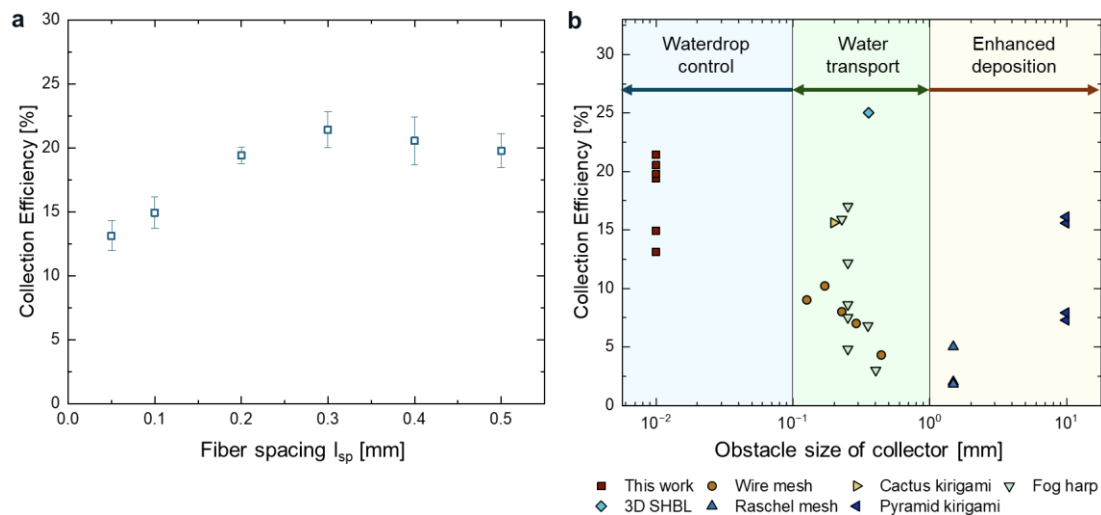


Figure 4.22. Measured water collection efficiency of micro-fiber grids. (a) Water collection efficiency for collectors with different fiber spacings. (b) Comparison of experimental water collection efficiency between this work to other reported structures with high efficiencies based on the obstacle size [12, 20, 29, 70, 80, 181]. The results of this work, wire mesh, fog harp, and Raschel mesh are measured in a closed chamber, the other results are measured in an open environment.

Notably, Figure 4.22b provides a perspective on current knowledge of improving water collection efficiency. As discussed in the introduction section, the strategies for improving efficiencies of fog collectors can be classified based on the obstacle size. For fog collectors with obstacles larger than 1 mm, enhancing the deposition of the fog droplets is necessary [21, 181, 188]. As the obstacle size reduces to 0.1~1 mm, surface modification and landscaping are widely studied to transport fog water out of collector to prevent the formation of water clogging [27, 31, 62, 70, 72, 81, 83, 162, 201-203]. This work pushes forward the size of obstacle to a

few micrometers, where the waterdrops can assist droplet capture due to their “visibility” if the waterdrop size is well controlled. Furthermore, the size and dispersion of waterdrops plays a key role in droplet capture, which requires further studies to understand the mechanism of waterdrop growth and shedding on micro-fibers, as well as to control the size and dispersion of waterdrops. The growth and shedding normally depend on the surface wettability of the collector, which should be studied in the future.

The exceptional water collection performance of micro-fiber grids is stable and independent on test conditions. The stability of the collector is evaluated through ten cycles of 1-hour collection test on micro-fiber grid with 0.5 mm spacing and 10  $\mu\text{m}$  fiber diameter. As shown in Figure 4.23a, the results indicate a stable water collection performance over 10 cycles with a minor drop of  $< 15\%$  in cycle 8-10. The structure of the grid basically maintains the geometry of square grids with noticeable distortions (see Figure 4.23b). The distortions are caused by the surface tension of collected water during the cycle of drying and harvesting, which drags the fibers to shrink the surface area of liquid water. In addition, the micro-fiber grid collectors are also tested in open environments to verify the impact of test conditions. As shown in Figure 4.23c, the grids of 0.3 mm and 0.5 mm spacing and 10  $\mu\text{m}$  fiber diameter are placed in fog flow of  $180 \text{ g h}^{-1}$  in an open environment. The results of the open environment test are similar to the closed chamber test with a 5% drop at the end of the 1-hour period, which is possibly caused by the disturbance from water evaporation and in-door ventilation. Therefore, the micro-fiber grid is promising in maintaining an efficient collection during long-term use and in a realistic condition for fog harvesting.

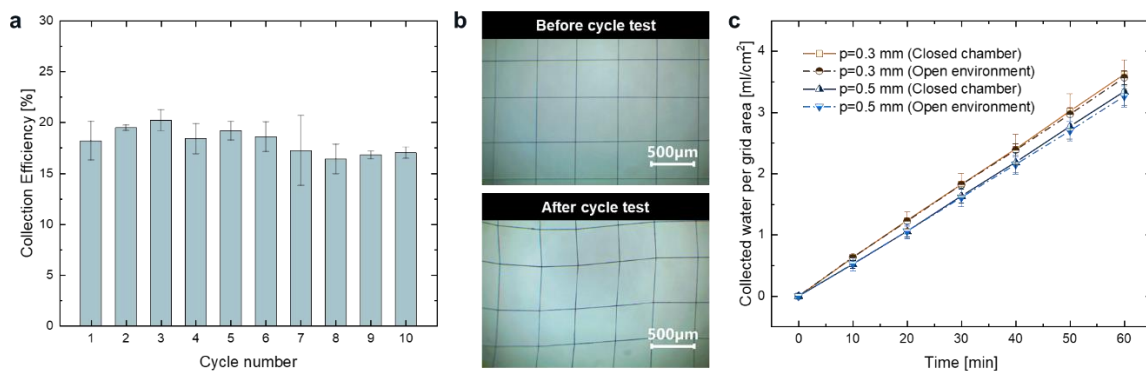


Figure 4.23. Cycle test and test condition impact. (a) Water collection efficiency of microfiber collector with 10  $\mu\text{m}$  diameter and 0.5 mm over 10 test cycles. (b) Microscopic image of the tested microfiber grids before and after 10 test cycles. (c) Water collection rate at the test condition of closed chamber and open environment.

In addition, the micro-fiber grid maintains its structural integrity, which contributes to withstanding large wind speeds and holding large amounts of waterdrops. As shown in Figure

4.24a, the micro-fiber grid collectors can withstand high air speeds of  $2.3\sim 4.6\text{ m s}^{-1}$ . The network structure of micro-fiber grids with  $0.5\text{ mm}$  fiber spacing and  $10\text{ }\mu\text{m}$  fiber diameter remains intact after 24 hours of test under  $4.6\text{ m s}^{-1}$  wind speed (see Figure 4.24b). Additionally, Figure 4.24c shows that a  $10\text{ cm}^2$  micro-fiber grid with  $0.3\text{ mm}$  spacing and  $10\text{ }\mu\text{m}$  fiber diameter can hold more than  $3\text{ g}$  liquid water on top of the grid. Furthermore, Figure 4.24d illustrates the tensile test results of micro-fiber grids with fiber diameter of  $10\text{ }\mu\text{m}$  and spacing of  $0.1\text{ mm}$ ,  $0.3\text{ mm}$  and  $0.5\text{ mm}$ , showing that the micro-fiber grid can elongate to 90% to 250% of its original length to resist mechanical impact. Therefore, the strength of micro-fiber grid is adequate for the purpose of fog harvesting at normal airflow and fog conditions.

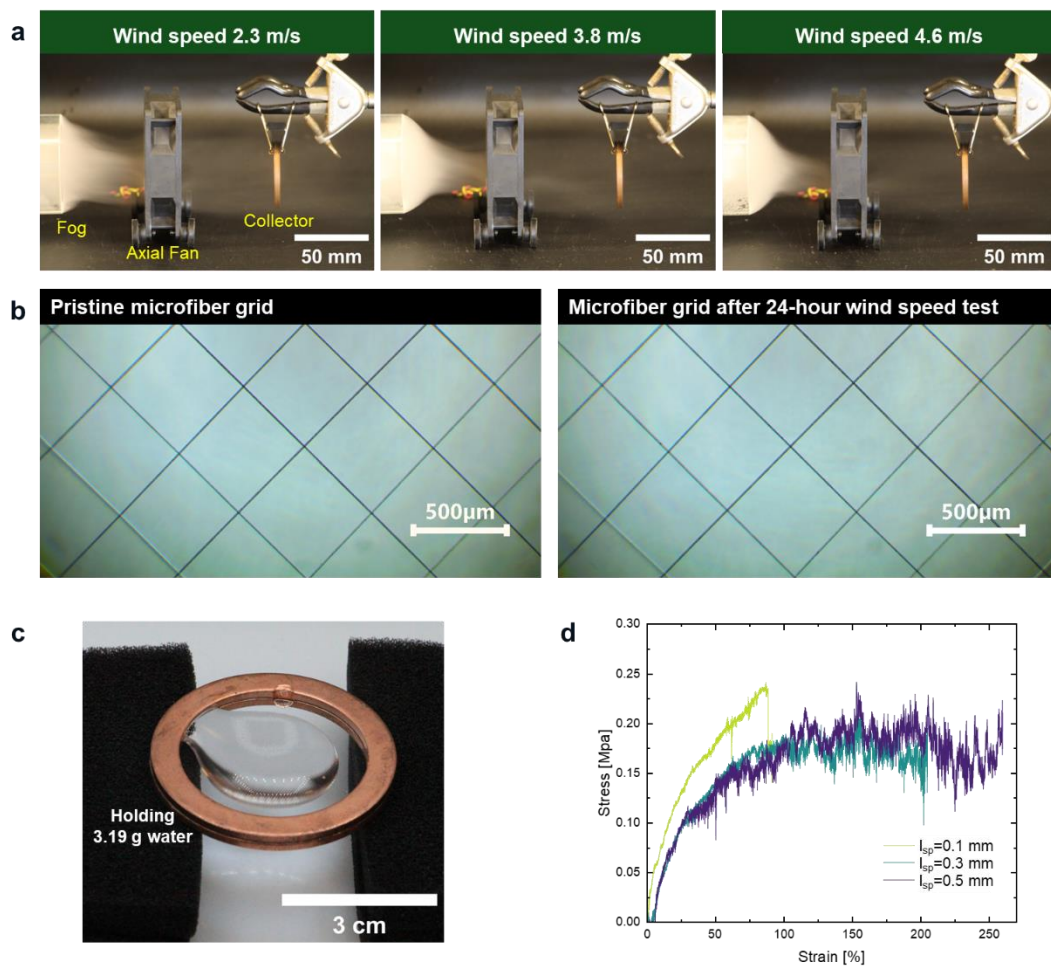


Figure 4.24. Structural integrity test of microfiber collector. (a) Windspeed durability test at windspeed of 2.3, 3.8 and  $4.6\text{ m s}^{-1}$ . (b) Microscopic image of tested microfiber grid before and after a 24-hour windspeed durability test at  $4.6\text{ m s}^{-1}$ . (c) Digital image of a  $10\text{ cm}^2$  collector holding 3.19 g water. (d) Tensile test results for microfiber grids.

Future improvements of micro-fiber grid are expected to enhance its durability and scalability, considering fog collectors require sufficient strength and large area to harvest more water from fog laden wind with high speed. Currently, the tensile strength of the PVDF-HFP

micro-fiber grid fabricated by NFES is  $\sim 20$  times lower than the dense PVDF-HFP fiber membrane fabricated by conventional electrospinning [204], as a result of sparse distribution and ultrafine thickness of fibers. To apply micro-fiber grid collectors in wind  $> 5 \text{ m s}^{-1}$ , durable materials with high intrinsic strength, such as metallic or ceramic fibers, should be explored to resist the drag of airflow. These strong fibers can be fabricated by multiple spinning technologies, including centrifugal spinning, electrospinning and solution blow spinning [205]. In addition, large scale applications such as fog collectors in field and drift catchers in cooling towers require scaling up the fabrication of micro-fiber grids. Therefore, scalable NFES technology with multiple spinnerets [97, 206] or techniques that can produce micro-fiber grids in large scale should be further studied and developed as future works.

## 4.5 Summary

In summary, this study investigates the effects of waterdrop on fog water collection when clogging the micro-fiber grids. Small waterdrops are “visible” to incoming airflow because of the thin fiber diameter, therefore effectively capturing the fog droplets. The growth of waterdrops, on the other hand, forms a pattern that deflects the airflow from large waterdrops to the satellite small ones, enhancing the fog capture on small waterdrops at low air velocity. As a result, the fog collector based on micro-fiber grids shows an outstanding collection efficiency of 21.4%. The micro-fiber collector is fabricated using exceedingly low amounts of inexpensive polymers without creating complex surface structures or chemical treatment, showing immense potential to collect fog water. Moreover, the micro-fiber based collector provides an effective strategy to increase the water collection efficiency - reducing the diameter of the solid structure to let waterdrops directly capture fog droplets.

## **Chapter 5 Plateau-Rayleigh Instability on Ribbon-like Fibers with Continuous Water Transport\***

From the previous chapters, the droplet capture on fiber-based fog collector is better understood through numerical and experimental studies. However, the ability of collectors to actively transport water holds significance for fog harvesting in actual environments. Fast transport of collected fog water can reduce the efficiency loss caused by water evaporation and droplet re-entrainment. Plateau-Rayleigh instability is the root cause of limited ability of water transport, because the formation of PRI waterdrops hinders the continuous film-wise flow along fibers. Therefore, this chapter experimentally investigates the PRI onset and water transport on fibers and fiber-based collectors.

### **5.1 Introduction**

Spontaneous liquid transport can drive the motion of liquid without the presence of external forces, fulfilling the demands for liquid flow in areas such as mass and heat transfer [207-211], separation [212-215], and energy conversion [216-219]. Diverse surfaces and structures have been developed to provide driving forces, such as fibers [27, 175], micropillars [220, 221], cones [222, 223], ratchets [224, 225], liquid diodes [209, 226], and complex hierarchical structures [31, 34, 35, 227]. Among them, flexible fiber materials are widely used for liquid transport by creating surface energy gradients through distinct morphologies [25-28, 81-83]. Due to the weavable nature, fiber materials capable of spontaneous liquid transport have important practical applications, including water harvesting [25, 26], sweat management [228-230], microfluidics [231, 232], and oil-water separation [212, 215].

Fog harvesting usually involves the continuous deposition of water on fibers as drifting droplets, which triggers Plateau-Rayleigh instability (PRI) and upsets water transport. The deposited droplets form a gradually thickening water film on the fiber surface, which is susceptible to environmental perturbations that develop to PRI [173]. PRI decomposes the film into drops, with the inter-drop distance determined by the PRI wavelength [54]. The resulting spherical PRI drops with a small surface area create local regions of low surface energy, which drives the water to accumulate in the drops rather than flow along the fibers [233], thus hindering the water transport over long distances.

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\* The contents in this chapter have been complied to a preprint at [arxiv.org/abs/2409.11607](https://arxiv.org/abs/2409.11607).

Propelling PRI drops along fibers is possible by introducing aerodynamic effects [185, 234], gradient texture [28], and conical structure [235, 236]. Unfortunately, drop-wise propulsion generally requires a force to overcome the threshold resistance caused by contact angle hysteresis [36], which is much larger than viscous friction in film-wise transport, thus limiting the continuous transport. Modifying the fiber structure[237, 238] or the surface tension of liquid [239] can effectively suppress the onset of PRI. However, these methods are only applicable when a limited amount of liquid is coated on fibers, which is difficult to satisfy the transport demand when water is continuously deposited on fibers. Therefore, achieving continuous film-wise transport is crucial to cope with water deposition.

Given that PRI generally occurs during the deposition of water, it is natural to consider how to effectively leverage the consequences of PRI. An interesting perspective is that the PRI drops are usually connected by a microscopic precursor film [23, 240, 241]; water droplets deposited on the precursor film is spontaneously transported to the nearby PRI drops [233]. Therefore, a reasonable hypothesis is that as long as the PRI wavelength is sufficiently long, continuous and spontaneous water transport over long distances can be achieved.

This study reports leveraging long-wave PRI for spontaneous and continuous water transport on ribbon-like fibers. The asymmetric curvature of the ribbon fibers causes the water film to spontaneously aggregate on the broad side of the fiber, which dominates the onset of long-wave PRI. The neighboring PRI drops are connected by water films, which transport water to the drops through a film-wise flow over centimeter scale distances. Interestingly, the film-wise transport contains a pair of opposing flows, which generates a row of shear-induced organized vortices and enhances flow mixing. Based on long-wave PRI, a rivulets-on-web structure is demonstrated to continuously transport water across a fiber web of 10 cm<sup>2</sup> area. This study envisions that the results have significance for the design of efficient fog collectors.

## **5.2 Experiment**

### **5.2.1 Preparation of cylindrical and ribbon-like glass fibers**

Cylindrical glass fibers are prepared by pulling heated glass capillary tubes using a butane torch (Cole-Parmer, Canada). For ribbon-like glass fibers, the heated glass capillary tubes are first pressed by a tweezer and then pulled. The size of fibers is measured by visualizing the cross section of fibers with microscope (AmScope SW-3T24Z, USA).

### 5.2.2 Preparation of ribbon-like polymeric fibers and fiber webs

Polymeric fibers and fiber webs are prepared using a near-field electrospinning (NFES) system. 2.5 g poly(vinylidene fluoride-co-hexafluoropropylene) (PVDF-HFP,  $M_w \sim 455,000$ , Sigma Aldrich, Canada) is dissolved into a mixture solvent of 3.75 g *N,N*-dimethylacetamide (DMAc, purity > 99.8%, Sigma Aldrich, Canada) and 3.75 g acetone (purity  $\geq 99.5\%$ , Fisher Scientific, Canada) to prepare a PVDF-HFP solution of 25 wt% concentration. 1 g polyacrylonitrile (PAN,  $M_w \sim 150,000$ , Sigma Aldrich, Canada) is dissolved into a mixture solvent of 4 g dimethyl sulfoxide (DMSO, purity > 99.9%, Sigma Aldrich, Canada) and 1.55 g acetone to prepare a PAN solution of 18 wt% concentration. The solutions are stirred overnight at room temperature.

The prepared polymer solutions are loaded into a 5 ml glass syringe (Hamilton, USA). The syringe is then connected to a 26 gauge metallic needle (Sigma Aldrich, Canada) and installed into the NFES system. The NFES system, which has been described in Chapter 4, deposits polymer solutions on a grounded collector at an electric voltage of 1.6 – 2 kV and a needle-to-collector distance of 1.5 – 2.5 mm. The collector translates along a programmed path to deposit polymer solutions, which further solidifies as single fibers or patterned fiber webs. The deposited wet solution on the flat collector spreads laterally, thus forming a ribbon-like morphology during solidification. The size of the ribbon-like fibers, i.e.,  $a$  and  $b$ , are controlled by tuning the flow rate of polymeric solution in the range of  $0.05 \text{ ml h}^{-1} - 0.2 \text{ ml h}^{-1}$  and the collector moving speed in the range of  $25 \text{ mm s}^{-1} - 150 \text{ mm s}^{-1}$ . The obtained ribbon-like fibers have the size in the range of  $10 \mu\text{m} < a < 45 \mu\text{m}$  and  $1 \mu\text{m} < b < 6 \mu\text{m}$ . The size of the fibers is measured by visualizing the cross section of fibers with scanning electron microscope (Zeiss FESEM 1530, Germany).

### 5.2.3 Experimental Setup

Experiments are conducted using a homemade wind tunnel. As shown in Figure 5.1, an axial fan (Noctua NV-FS2, Austria) is installed at the inlet of the tunnel to generate airflow. The fan speed is controlled by a DC power supply that regulates voltage from 5V – 12 V. The airflow is conditioned using a tube-bundle flow straightener to eliminate the swirls generated by the axial fan. An ultrasonic humidifier injects droplets of deionized water into the airflow, providing a continuous supply of water flux that is tunable in the range of  $4 \mu\text{m s}^{-1} - 37 \mu\text{m s}^{-1}$ . Ducts and contractions are used to connect the above components to complete the wind tunnel. The airflow velocity inside the tunnel can be adjusted within the range of  $1.4 - 2.2 \text{ m s}^{-1}$  by controlling the fan speed, which is measured using a hotwire anemometer (TPI, 575C1, USA).

However, the velocity is kept as  $2 \text{ m s}^{-1}$  throughout this work because it imposes negligible influence on test results. A digital camera (Cannon R5, Japan) attached to a microscope (AmScope SW-3T24Z, USA) is placed at the rear side of the tunnel for visualization. Dimensions of the wind tunnel are also provided in Figure 5.1.

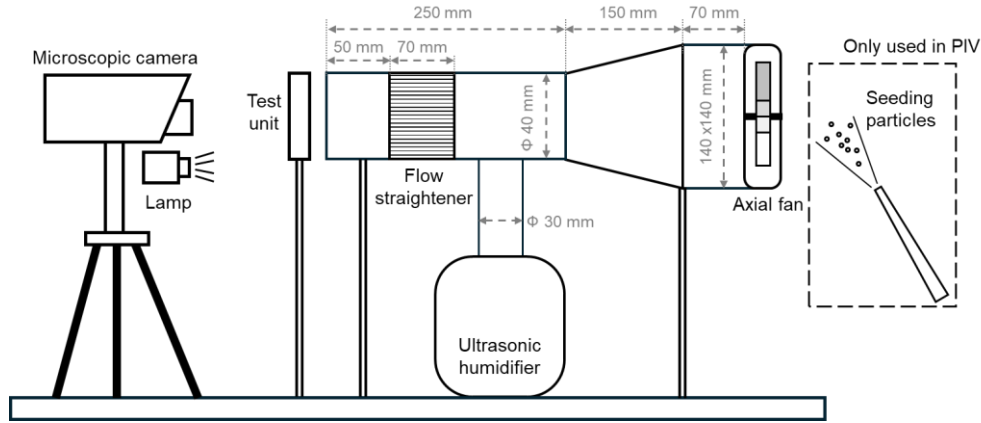


Figure 5.1. Schematic of configurations and dimensions of the wind tunnel used for this study.

The PRI wavelength on fibers is measured as the distance between two neighboring PRI drops. The tested fiber is placed at the outlet of the wind tunnel so that droplets can continuously deposit on fibers. Before each test, the fiber is immersed in the droplet-laden airflow for at least 1 minute to ensure an even coating of water film. Then, any formed drops on the fiber are removed by a gentle airflow, leaving a residual film on the tested fibers. During the test, the film gradually grows until PRI occurs and decomposes into drops. The microscopic camera records the image when the number of PRI drops stops increasing. The recorded images are processed to measure the inter-drop distance as the PRI wavelength.

The water transport on ribbon-like fibers is characterized by particle-image velocimetry (PIV). The tested ribbon-like glass fibers are put in a droplet flux of  $14 \text{ } \mu\text{m s}^{-1}$  to trigger PRI onset, and the flux is reduced to  $4 \text{ } \mu\text{m s}^{-1}$  for flow seeding with better image quality. The transparent glass fiber allows the camera to record the film flow on the rear side that receives droplet flux. Polystyrene microspheres with diameters of  $10 \text{ } \mu\text{m}$  are used as trace particles to visualize the flow. The particles are screened using a  $53 \text{ } \mu\text{m}$  sieve (W.S. Tyler, Canada) to remove large clumps, and then delivered to the inlet of wind tunnel by compressed gas. The airflow inside the tunnel carries the particles to impact the tested fiber, thus seeding the water film. A fiber-optic lamp (Cole-Parmer, Canada) is placed parallel with the objective lens of the microscope to illuminate the particles. After the delivery of particles, the microscopic camera

records videos of film flow on tested fiber at a frame rate of 120 fps. Notably, the film is sparsely seeded with a number density of  $200 - 300 \text{ mm}^{-2}$  to avoid particle buildup.

The recorded video is processed using the MATLAB toolbox PIVlab 3.01. This study uses a multi-pass linear window deformation technique: the first pass used a  $32 \times 32$ -pixel interrogation window, the second pass  $16 \times 16$ -pixel interrogation window and sub-pixel displacement is estimated by two-dimensional Gaussian regression. Due to the sparse seeding, the algorithm of ensemble correlation is used to process 500 consecutive image pairs for better signal-to-noise ratio. The values of valid detection probability for all PIV results are above 0.95.

The accuracy of PIV analysis relies on the ability of trace particles to follow the flow streamlines. The obedience of particle trajectories to the streamlines is characterized by the Stokes number  $Stk$ . Specifically, accurate resolving of flow structures with errors below 1% requires  $Stk < 0.1$ . Using this value together with the particle diameter of  $10 \text{ }\mu\text{m}$ , a maximum flow velocity of  $10 \text{ mm s}^{-1}$ , water density of  $1 \text{ g cm}^{-3}$  and viscosity of  $0.89 \text{ mPa s}$ , the minimal length of flow structure that can be accurately resolved is calculated as  $1.25 \text{ }\mu\text{m}$ , which is sufficiently small compared to the size of the PIV interrogation windows. Therefore, this PIV analysis can resolve micrometer-scale flow structures with accuracy errors below 1%.

### 5.3 Results and Discussion

During the deposition of water on fibers, the onset of PRI is based on the fastest growing mode of environmental perturbations. As shown in Figure 5.2a, the deposited water forms a thin film with a thickness  $h$  wrapping around the fiber. Environmental perturbations, existing as a series of sinusoidal modes, create crests and troughs on the liquid-vapor interfaces. The trough interface generates greater capillary pressure in liquid phase than the crest interface, driving water flows towards the crest. The capillary-driven flow further increases the pressure difference between the crest and the trough, and eventually decomposes the film into drops connected by precursor films. Linear stability analysis shows that a single mode with wavelength  $\lambda$  has the fastest growth rate, thus dominating the final inter-drop distance [53]. For a cylindrical fiber with a radius  $a$ , the thin water film ( $h \ll a$ ) develops PRI with the dominating wavelength  $\lambda$  and characteristic growth time  $\tau_p$  as follows:

$$\lambda = 2\pi\sqrt{2}a \quad (100)$$

$$\tau_p = \frac{12\mu_w a^4}{\gamma h^3} \quad (101)$$

where  $\mu_w$  and  $\gamma$  are the viscosity and surface tension of water. Despite being limited to cylindrical fibers, Eqs. (100) and (101) reveals two important characteristics of PRI: (a) the dominating wavelength is controlled by the surface curvature of the fiber, and (b) the thickness of water film determines the growth rate of PRI.

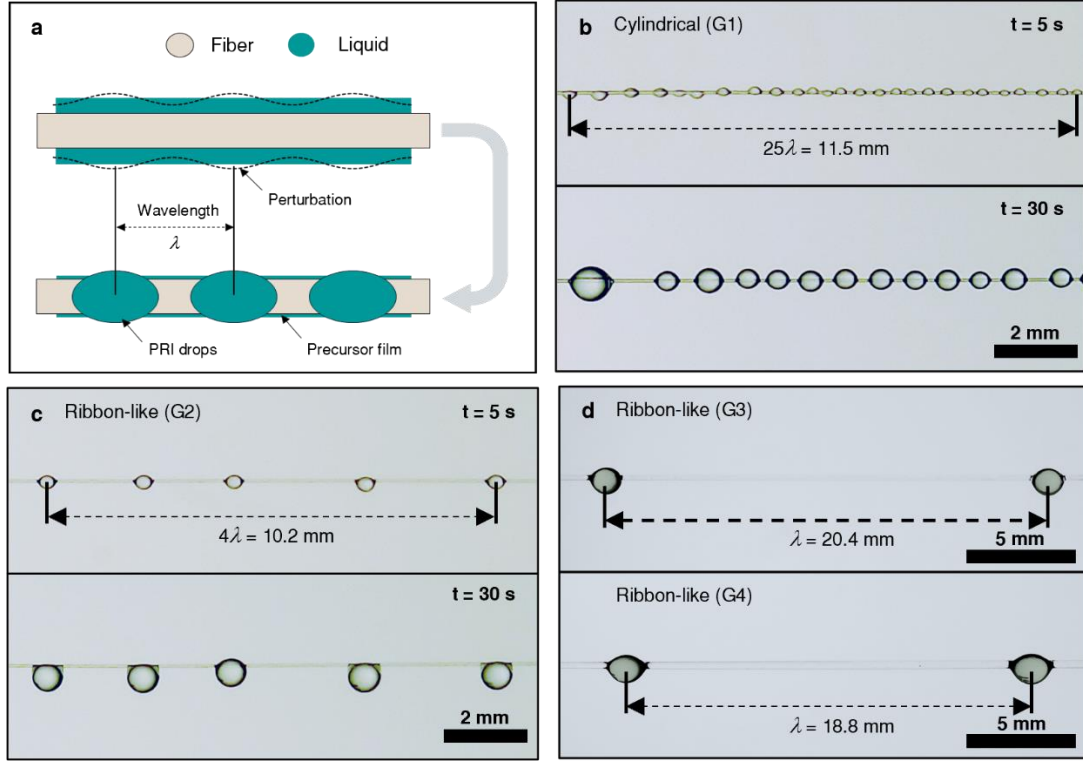


Figure 5.2. PRI on cylindrical and ribbon-like fibers during water deposition. (a) Schematic of PRI on a fiber developing from the perturbed water film to the decomposed waterdrops. (b-d) Digital images of PRI drop formed when exposing glass fibers to water deposition at a flux of  $14 \mu\text{m s}^{-1}$ : (b) cylindrical glass fiber (G1,  $a = 41 \mu\text{m}$ ) exposed for 5 seconds and 30 seconds; (c) ribbon-like glass fiber (G2,  $a = 41 \mu\text{m}$ ,  $b = 18 \mu\text{m}$ ) exposed for 5 seconds and 30 seconds; (d) ribbon-like glass fibers (G3,  $a = 117 \mu\text{m}$ ,  $b = 23 \mu\text{m}$ ; G4,  $a = 160 \mu\text{m}$ ,  $b = 43 \mu\text{m}$ ) exposed for 30 seconds.

Due to varying surface curvature, cylindrical and ribbon-like fibers exhibit distinct PRI wavelength. Figure 5.2b shows the PRI drops on a cylindrical glass fiber (G1) with  $a = 41 \mu\text{m}$  after 5 seconds and 30 seconds of exposure to a water flux of  $14 \mu\text{m s}^{-1}$ . At 5 seconds, a film with a length of 11.5 mm is decomposed into 26 small PRI drops, indicating a dominating PRI wavelength of  $0.46 \pm 0.12$  mm. This wavelength agrees with the theoretical wavelength calculated using Eq. (100), but with an average increase of 26%. Similarly, Haefner et al. reported an average 28% increase in PRI wavelength on cylindrical glass fiber compared to their theoretical model [54], which is attributed to the experimental contribution of several

perturbation modes. Continuously exposing the fiber to the water flux, the number of PRI drops reduces from 26 to 12 at 30 seconds due to drop growth. Specifically, the water deposition increases the radius of PRI drops to greater than half of the PRI wavelength, which causes neighboring drops to merge with each other and reduce the number of drops.

In contrast, the water film on ribbon-like fibers can develop PRI with longer wavelengths, enabling spontaneous film-wise transport. A ribbon-like glass fiber (G2) with a major radius of  $a = 41\ \mu\text{m}$  and a minor radius of  $b = 18\ \mu\text{m}$  is tested in the same condition as G1. The aspect ratio of the ribbon-like fiber,  $\varepsilon = b/a = 0.439$ , represents the flatness of the cross section. As shown in Figure 5.2c, the dominating wavelength measured after 5 seconds of exposure is  $2.55 \pm 0.43\ \text{mm}$ , which is 6 and 15 times longer than the theoretical wavelength calculated with fiber radius of  $a$  and  $b$ , respectively. In addition, despite the continuous water deposition, the number of drops remains unchanged after 30 seconds of exposure, indicating no occurrence of consecutive PRI between two neighboring drops. Together with the increasing drop volume, the constant number of drops evidences the spontaneous film-wise transport of water to the PRI drops over millimeter-scale distances.

Further increasing the major radius and reducing the aspect ratio of ribbon-like fibers leads to the PRI wavelength and film-wise transport in centimeter scale. As shown in Figure 5.2d, the same condition is used to test two “flat” ribbon-like fibers G3 ( $a = 117\ \mu\text{m}$ ,  $b = 23\ \mu\text{m}$ ) and G4 ( $a = 160\ \mu\text{m}$ ,  $b = 43\ \mu\text{m}$ ), corresponding to the aspect ratio  $\varepsilon$  of 0.196 and 0.269, respectively. The deposited water develops PRI of wavelength of 20.4 mm and 18.8 mm. In addition, the inter-drop distance determined by the wavelength remains unchanged after 30 seconds of exposure, indicating the centimeter-scale film-wise transport. The increased wavelength from millimeter scale to centimeter scale is mainly because the major radius,  $a$ , of G3 and G4 is 2.9 and 3.9 times greater than that of G2. Meanwhile, the aspect ratio also affects the wavelength, because G3, with a smaller aspect ratio, has a longer PRI wavelength than G4, despite G4 having a larger major radius.

Ribbon-like fibers of varied sizes and materials show similar characteristics of long-wave PRI. The same condition is used to test fibers with the size in the range of  $10\ \mu\text{m} < a < 400\ \mu\text{m}$  and  $1\ \mu\text{m} < b < 265\ \mu\text{m}$ . The tested fibers are made of glass, polyacrylonitrile (PAN), and poly(vinylidene fluoride-co-hexafluoropropylene) (PVDF-HFP) with distinct wettability. Figure 5.3a summarizes the PRI wavelength of fibers according to their mean fiber radius  $(a + b)/2$  for a better comparison to cylindrical fibers. Regardless of fiber material, the PRI

wavelengths for ribbon-like fibers are all longer than the theoretical wavelength for cylindrical fibers, indicating the characteristics of long-wave PRI. Most importantly, the wavelength is related to the aspect ratio, where the wavelengths for ribbon-like fibers with  $\varepsilon < 0.5$  are generally larger than that with  $\varepsilon > 0.5$ . Therefore, the long-wave PRI is based on the flat morphology of fiber cross section, instead of the specific value of radius or the material wettability.

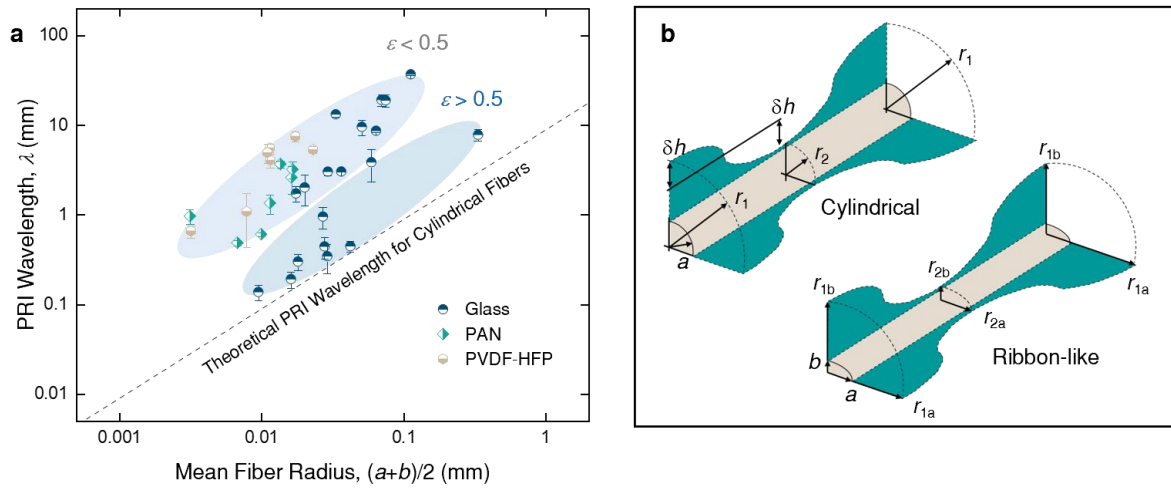


Figure 5.3. PRI wavelength for cylindrical and ribbon-like fibers. (a) Plot of PRI wavelength as a function of mean fiber radius  $(a+b)/2$ . (b) Schematic of perturbed liquid-vapor interface on the cylindrical and ribbon-like fiber. Data points and error bars in (c) indicate mean values  $\pm$  s.d. of four measurements.

A reasonable speculation is that the long-wave PRI and the resultant film-wise transport is based on the non-axisymmetric curvature of the ribbon-like fibers. As shown in Figure 5.3b, for the cylindrical fiber, the perturbation of liquid-vapor interface with a magnitude of  $\delta h$  is axisymmetric, leading to an even distribution of capillary pressure  $p \sim \gamma/r$  along the circumference of the fiber. As a result, the capillary pressure along the fiber axis is mainly determined by the radius of curvature at the crest and the trough, i.e.,  $r_1 = a + h + \delta h$  and  $r_2 = a + h - \delta h$ , indicating that the fiber radius,  $a$ , controls the PRI wavelength when  $h \ll a$ . In contrast, the non-axisymmetric curvature of ribbon-like fibers leads to the uneven distribution of capillary pressure along the fiber circumference, which is controlled by the principal radii of curvature of the water film, i.e.,  $r_{1a}$ ,  $r_{1b}$ ,  $r_{2a}$  and  $r_{2b}$ . Therefore, it is important to understand how curvature affects the PRI wavelength and the resultant film-wise transport on ribbon-like fibers.

### 5.3.1 Long-wave PRI on ribbon-like fibers

The non-axisymmetric curvature induces a circumferential pressure difference, which varies the thickness of water film around the ribbon-like fiber. The cross section of the ribbon like fiber can be approximated as an ellipse with major and minor semiaxis of  $a$  and  $b$ . As shown in Figure 5.4a, the thin film ( $h \ll a$ ) wrapping around the ribbon-like fiber leads to an uneven distribution of capillary pressure, i.e.,  $p_1 = \gamma/(b^2/a)$  at the narrow side (shoulder) and  $p_2 = \gamma/(a^2/b)$  at the broad side (belly). The circumferential pressure difference drives water flowing from the shoulder to the belly. As a result, the deposited water gradually aggregates on fiber belly. The similar phenomenon has been observed in nature, where butterflies and moths, when feeding on liquid nectar, aggregate the liquid on the broad side of their flattened proboscises [242]. Therefore, the non-axisymmetric curvature drives circumferential capillary flow, resulting in a thicker film on fiber belly and a thinner film on fiber shoulder.

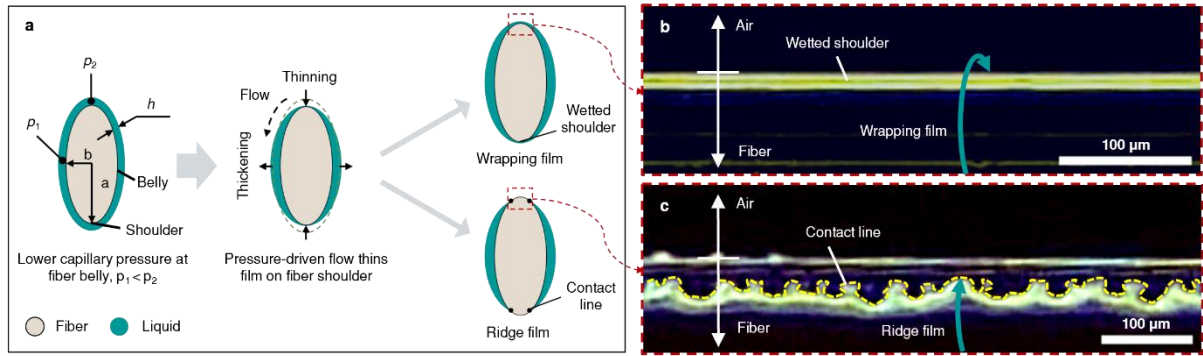


Figure 5.4. Water film morphology on ribbon-like fibers. (a) Schematic of the variation of film thickness along the circumference of the ribbon-like fibers and the resulting two possible film morphologies. (b-c) Digital microscopic image of the film morphologies on the shoulder of ribbon-like glass fibers with the sizes of  $a = 59 \mu\text{m}$ ,  $b = 7.5 \mu\text{m}$  (b), and  $a = 196 \mu\text{m}$ ,  $b = 27.5 \mu\text{m}$  (c).

The variation of film thickness leads to two possible morphologies of water film – wrapping film and ridge film. The wrapping morphology is formed when the film remains intact to wet the fiber shoulder. As shown in Figure 5.4b, the shoulder of a ribbon-like fiber ( $a = 59 \mu\text{m}$ ,  $b = 7.5 \mu\text{m}$ ,  $\varepsilon = 0.13$ ) is wetted by water, allowing the film to wrap around the fiber. In contrast, the thinned water film on fiber shoulder can be ruptured when the capillary pressure difference overcomes the conjoining pressure between the liquid-vapor and liquid-solid interface [243]. The ruptured film retracts from the shoulder, forming a contact line for the vapor, liquid and solid phases. As shown in Figure 5.4c, the water film retracting from the shoulder of a ribbon-like fiber ( $a = 196 \mu\text{m}$ ,  $b = 27.5 \mu\text{m}$ ,  $\varepsilon = 0.14$ ) develops a dewetting pattern with a sinuous contact line, which is caused by the instability of the water rim [244]. As a result, a water ridge is formed on the fiber belly.

The characteristic timescale of the thickness variation and PRI are compared to investigating whether the thinning of the shoulder film affects the onset of PRI. The timescale of PRI for shoulder film,  $\tau_p$ , can be estimated by Eq. (101) using the radius of  $b$ . The timescale for the thinning of the shoulder film,  $\tau_{th}$ , is estimated using the lubrication approximation as follows. First, assuming  $h \ll a$ , the capillary pressure difference between the belly and shoulder film can be calculated using the respective radius of curvature.

$$p_1 - p_2 = \gamma \frac{a^3 - b^3}{a^2 b^2} \quad (102)$$

On the other hand, the velocity of capillary flow that thins the shoulder film can be calculated as follows using the lubrication approximation.

$$u_{th} = -\frac{h^2}{3\mu_w} \nabla p \quad (103)$$

Linearizing the pressure gradient as  $(p_1 - p_2)/(a + b)$  gives

$$u_{th} = -\frac{\gamma h^2 (a^3 - b^3)}{3\mu_w a^2 b^2 (a + b)} \quad (104)$$

Then, the time scale of film thinning at fiber shoulder can be estimated as

$$\tau_{th} = \frac{a + b}{|u_{th}|} \quad (105)$$

Dividing  $\tau_p$  by  $\tau_{th}$  leads to the relative timescale of PRI and film thinning as follows.

$$\frac{\tau_p}{\tau_{th}} > \frac{\tau_{pc}}{\tau_{th}} = \frac{4}{\sqrt{2} - 1} \frac{(1 - \varepsilon^3)}{\sqrt{\varepsilon}(1 + \varepsilon)^2} \quad (106)$$

where  $\tau_{pc}$  is the timescale of PRI for film with critical thickness  $h_c = b(\sqrt{2}-1)$ , which corresponds to the maximum thickness of film to maintain stable ( $h < h_c$ ) [173, 233]. As shown in Figure 5.5, the film thinning always occurs faster than PRI as long as the aspect ratio is less than 0.9. The fast thinning further increases the timescale of PRI for shoulder film because of  $\tau_p \sim h^{-3}$ , thus suppressing the onset of PRI on fiber shoulder. Therefore, the onset of PRI on ribbon-like fibers is dominated by the thickened water film on fiber belly.

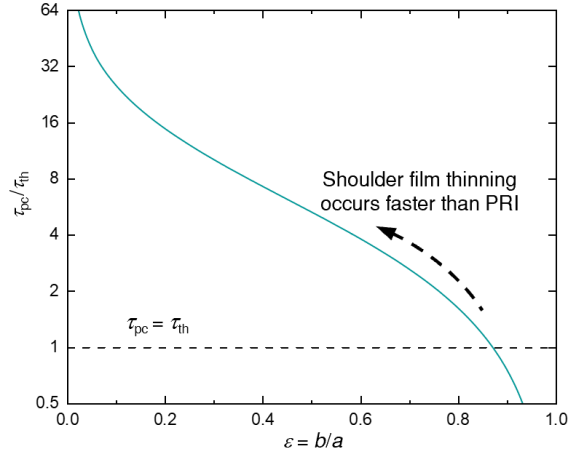


Figure 5.5. Plot of the ratio of characteristic timescale for PRI and shoulder film thinning,  $\tau_{pc}/\tau_{th}$  as a function of fiber aspect ratio,  $\epsilon$ .

Based on dominating PRI on fiber belly, the theoretical PRI wavelength can be derived for the wrapping and ridge films. The derivation is based on the principle that the wavelength is controlled by the surface curvature, while avoiding the complicated mathematical description of the 3D non-axisymmetric geometry. The dominating wavelength for wrapping film and ridge film relies on the radius of curvature  $\zeta$  for fiber belly, which is expressed as

$$\zeta = \frac{a^2}{b} \quad (107)$$

Starting from  $\zeta$ , the theoretical wavelength for the two film morphologies can be derived in the contents below.

For wrapping films, the equation of dominating wavelength  $\lambda$ , i.e., Eq. (100), is adopted using  $\zeta$  as the equivalent fiber radius, written as

$$\frac{\lambda}{\zeta} = 2\pi\sqrt{2} \quad (108)$$

Substituting  $\zeta$  with  $a$  and aspect ratio  $\epsilon = b/a$  gives the theoretical wavelength for wrapping film as follows.

$$\Lambda = \frac{\lambda}{a} = \frac{2\pi\sqrt{2}}{\epsilon} \quad (109)$$

For ridge films, the perturbation needs to move the contact line to deform the film, therefore the viscous dissipation at moving contact lines should be included. First, the

following dispersion relation derived by Diez et al. [245] is used for the growth of PRI on liquid ridge.

$$\omega = q_0^2 - q_0^4 \quad (110)$$

where  $\omega$  and  $q_0$  are the dimensionless growth rate and wave number of the perturbation. Eq. (110) gives the dominating wave number  $q^2 = 1/2$  corresponding to the maximum growth rate where  $d\omega/dq_0 = 0$ , and the critical wave number  $q_c^2 = 1$  corresponding to the marginal growth rate where  $\omega = 0$ . Therefore, a relationship between the dominating and critical wave numbers is obtained as follows.

$$q = \frac{q_c}{\sqrt{2}} \quad (111)$$

As a result, the dimensional wavelength must obey the following relationship.

$$\lambda = \sqrt{2}\lambda_c \quad (112)$$

Then, the critical wavelength  $\lambda_c$  is obtained from Langbein's stability criterion of liquid column on a solid plane with moving contact lines [246], which is written as

$$\frac{\lambda_c}{\xi_r} = 2\pi \sqrt{\frac{\pi}{\alpha}} \quad (113)$$

where  $\xi_r$  is the radius of curvature of the column, and  $\alpha$  is the angle between the plan and liquid-vapor interface. Considering the thin ridge film as a thin shell of the liquid column leads to  $\xi_r \approx \xi$  and  $\alpha \approx \arcsin(\varepsilon)$ . Therefore, Eq. (113) can be rewritten as

$$\frac{\lambda_c}{a} = \frac{2\pi}{\varepsilon} \sqrt{\frac{\pi}{\arcsin \varepsilon}} \quad (114)$$

Using Eq. (112), the dominating wavelength for ridge film is obtained as follows.

$$\Lambda = \frac{\lambda}{a} = \frac{2\pi}{\varepsilon} \sqrt{\frac{2\pi}{\arcsin \varepsilon}} \quad (115)$$

Together, Eq. (109) and (115) suggests that the ridge film has a longer PRI wavelength than the wrapping film because the aspect ratio  $\varepsilon$  is smaller than 1. The longer wavelength indicates the stabilizing effect of the contact line on PRI with shorter wavelength, where the perturbations are damped by the viscous dissipation at the moving contact line. In addition,

taking  $\varepsilon$  to 0 gives an infinitely long wavelength for both film morphologies, implying that the water film on an extremely flat ribbon-like fiber can maintain stable without the onset of PRI. This extreme case is surprisingly reasonable because the sharp shoulder with  $\varepsilon = 0$  tends to pin the contact line from moving, thus stabilizes the water film from decomposing into drops, which agrees with the theoretical results of Davis [247].

Both preceding theoretical forms of the dominating PRI wavelength are related to the aspect ratio, allowing convenient comparison with the experimental results. As shown in Figure 5.6a, the wavelengths for most tested fibers are within the region bounded by curves of Eq. (109) and (115). Therefore, the long-wave PRI is satisfactorily explained by the preceding theoretical analysis. In addition, the wavelengths for most glass fibers are centered around the theoretical value of ridge film, whereas the polymeric fibers are scattered towards the curve of wrapping film. The reason for the scattered distribution is that polymeric fibers have rougher surface compared to the smooth glass fibers, which provides more surface for the attachment of water and prevents the rupture of the shoulder film [243]. Overall, the non-axisymmetric curvature of the ribbon-like fibers drives the deposited water to aggregate on the fiber belly of small curvature, leading to the onset of long-wave PRI.

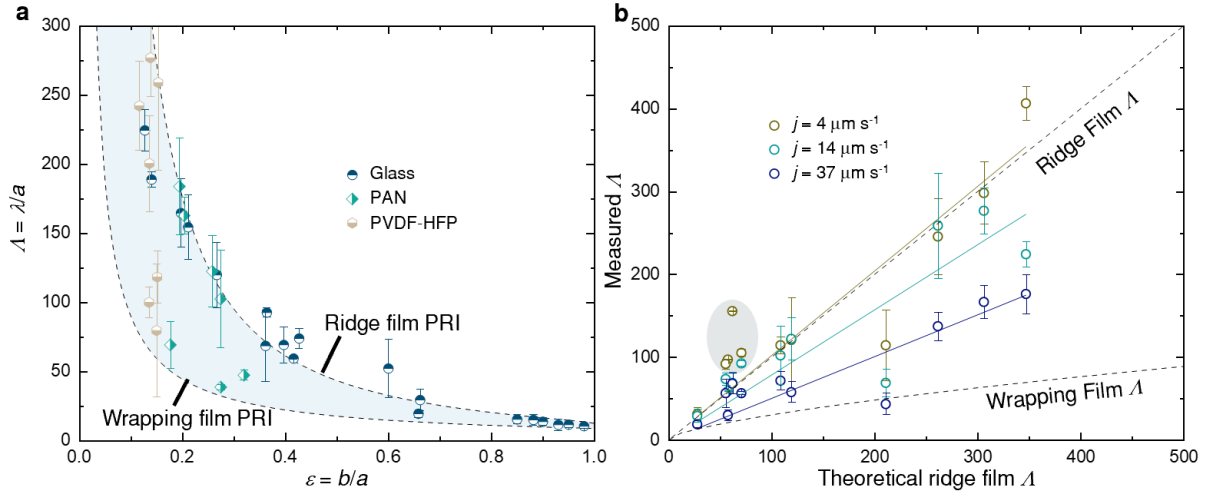


Figure 5.6. Long-wave PRI on ribbon-like fibers. (a) Plot of the dimensionless PRI wavelength,  $\Lambda$ , as a function of fiber aspect ratio,  $\varepsilon$ , using the experimental data and the derived PRI wavelength for wrapping and ridge film. (b) Plot of measured  $\Lambda$  as a function of the theoretical  $\Lambda$  for ridge film at the water flux,  $j$ , of 4 – 37  $\mu\text{m s}^{-1}$ . The colored solid lines in (b) are the best linear fitting of the measured  $\Lambda$ . Data points and error bars in (a) and (b) indicate mean values  $\pm$  s.d. of four measurements.

Notably, a shift in wavelength occurs when the flux of water deposition varies. As shown in Figure 5.6b, the increasing flux generally reduces the measured  $\Lambda$  within a region bounded by the theoretical  $\Lambda$  for the ridge film and the wrapping film. At the water flux of  $j = 4 \mu\text{m s}^{-1}$ ,

the fitting line of the measured  $\lambda$  is closer to the theoretical value of the ridge film, whereas the line shifts towards the wrapping film curve at the flux of  $j = 37 \mu\text{m s}^{-1}$ . The shift takes place because the larger water flux can replenish the thinning film at the fiber shoulder, preventing a wrapping film from rupturing into a ridge film. In addition, the measured  $\lambda$  at  $j = 4 \mu\text{m s}^{-1}$  increases to systematically deviate from the bounded region when theoretical  $\lambda < 100$  (grey circle area). The deviation is attributed to the size difference of the PRI drops, where larger drops consumes the smaller ones due to their different capillary pressure [248]. For two closely distanced drops with  $\lambda < 100$ , the increased capillary suction amplifies the inter-drop consumption when a small flux  $j = 4 \mu\text{m s}^{-1}$  cannot replenish the rapidly depleting water of smaller drops. As a result, the larger drop “eats” the smaller one, which appears as the increased wavelength.

### 5.3.2 Characteristics of film-wise water transport

After PRI occurs, the precursor film between PRI drops receives deposited water, developing to a flowing film that continuously transports water to neighboring PRI drops. As shown in Figure 5.7, the deposited water has high surface energy and tends to reduce its surface by curling into a drop, yielding a capillary pressure,  $p_1$ . Compared to the water film, the existing PRI drops with a radius  $r$  have lower surface energy and a smaller capillary pressure,  $p_2$ . The pressure difference  $\Delta p = p_1 - p_2$  over a distance of half of the PRI wavelength,  $\lambda/2$ , exerts a suction force on the film, which drives the film-wise flow towards the PRI drops.

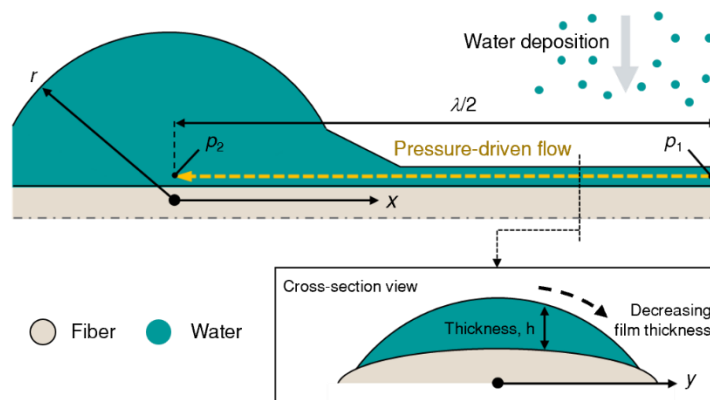


Figure 5.7: Schematic of water transport from the film to the PRI drop. The figure inset provides a cross-section view of the water film.

The particle image velocimetry (PIV) test of two ribbon-like glass fibers, RG1 ( $a = 196 \mu\text{m}$ ,  $\varepsilon = 0.14$ ) and RG2 ( $a = 117 \mu\text{m}$ ,  $\varepsilon = 0.2$ ), reveals that the film-wise transport consists of a pair of opposing flows. The test condition (see Methods) triggers PRI on RG1 and RG2 with a dominating wavelength of  $\lambda = 37 \text{ mm}$  and  $19 \text{ mm}$ , forming PRI drops with different radius

(RG1:  $r_1 = 0.56$  mm,  $r_2 = 0.96$  mm; RG2:  $r_1 = 0.70$  mm, and  $r_2 = 0.83$  mm; 1 and 2 denote principle radii). As shown in Figure 5.8a-b, the vector field and velocity magnitude of film-wise flow are depicted using dimensionless coordinates of  $X = x/a$  and  $Y = y/a$ . Generally, the film-wise flow exists on both RG1 and RG2 with a velocity magnitude in the range of  $0.05$  mm  $s^{-1}$ – $0.7$  mm  $s^{-1}$  and  $0.1$  mm  $s^{-1}$ – $2.2$  mm  $s^{-1}$ , respectively. Specifically, the water near the fiber belly flows towards the PRI drop at a higher velocity, i.e., the forward flow, due to the suction force generated by the film-drop pressure difference. In contrast, the water near the fiber shoulder flows away from the PRI drop at a lower velocity, i.e., the backward flow, which is caused by the shape of the water film and explained later.

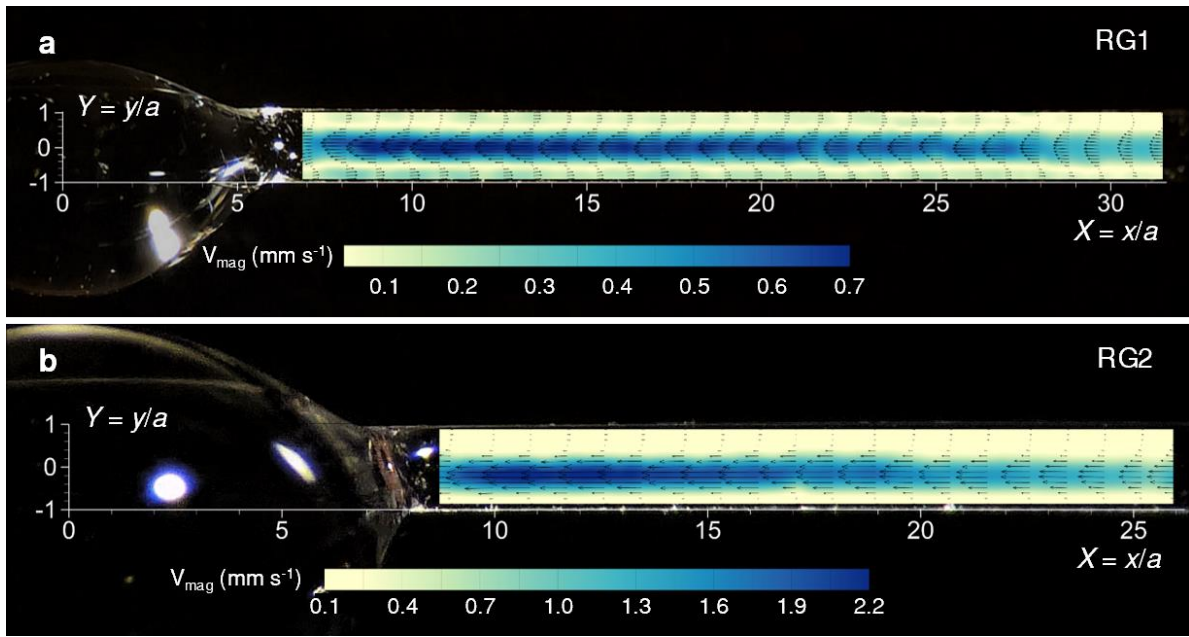


Figure 5.8. PIV results of velocity vector (arrow) and magnitude (contour) for the film-wise flow on two ribbon-like fibers of RG1 ( $a = 196$   $\mu\text{m}$ ,  $\varepsilon = 0.14$ ; b) and RG2 ( $a = 117$   $\mu\text{m}$ ,  $\varepsilon = 0.2$ ; c).

Figure 5.9a shows the profile of  $X$  component of the velocity,  $u$ , across the  $Y$  axis at  $X = 10, 15, 20, 25$ . Here, the plus/minus sign of  $u$  is intentionally reversed for better presentation. Using RG1 as an example,  $u$  maintains positive for the forward flow within the range of  $0.6 < Y < 0.6$  and reaches the highest  $u_f \approx 0.5$  mm  $s^{-1}$ – $0.75$  mm  $s^{-1}$  when  $Y \approx 0$ , following a symmetric Poiseuille-flow profile. The profile is based on the circular shape of the film cross section (see inset of Figure 5.7a), where the film is thickest at  $Y \approx 0$  and thinner when approaching the fiber shoulder. The thin shoulder film is subjected to the viscous boundary layer at the liquid-solid interface, which decreases the flow velocity. In addition, the backward flow occurs when  $|Y| > 0.6$ , and the velocity reaches maximum of  $u_b \approx -0.1$ – $-0.3$  mm  $s^{-1}$  at  $|Y| \approx 0.7$ . Furthermore, the profile of  $u$  is shifted towards the lower shoulder ( $Y = -1$ ) of RG2. The shifting of velocity

profile is due to the mass center of the heavy PRI drop sagging below the centerline of RG2 by gravity, thereby lowering the suction position.

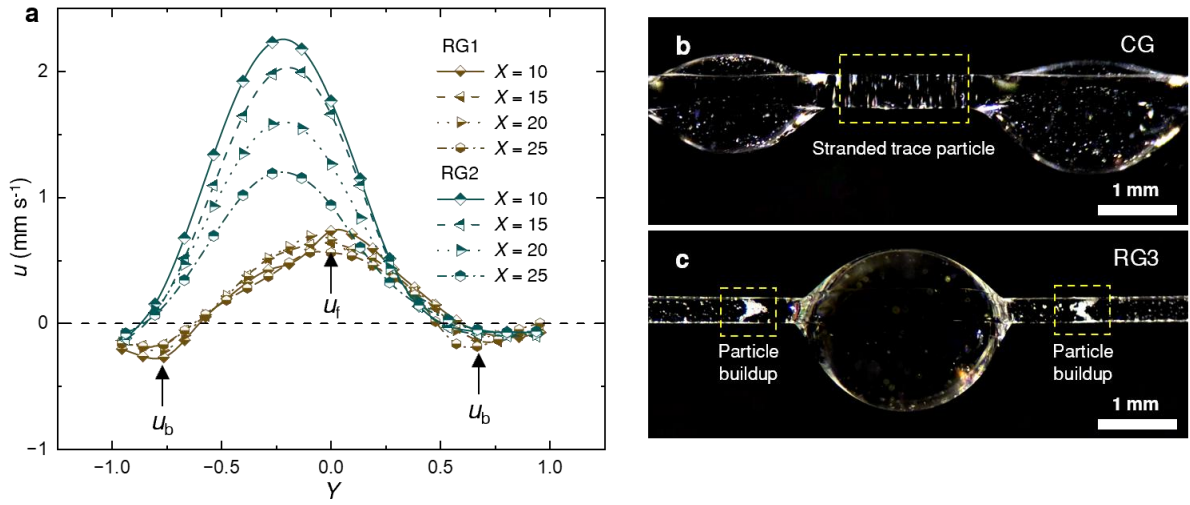


Figure 5.9. Velocity profile and particle stranding. (a) Plot of the  $X$  component of the flow velocity,  $u$ , as a function of  $Y$ . (b-c) Digital microscopic images of trace particles on CG (cylindrical glass fiber,  $a = 125 \mu\text{m}$ ; b) and RG3 (ribbon-like glass fiber,  $a = 94 \mu\text{m}$ ,  $\varepsilon = 0.36$ ; c).

The water film on a cylindrical fiber (CG,  $a = 125 \mu\text{m}$ ) and a rounder ribbon-like fiber (RG3,  $a = 94 \mu\text{m}$ ,  $\varepsilon = 0.36$ ) is also seeded to visualize the flow. However, the film on the cylindrical fiber is too thin to drift the trace particles with the diameter of  $10 \mu\text{m}$ , therefore the particles appear to be “stranded” (see Figure 5.9b). Similarly, RG3 generates a thinner film compared to RG1 and RG2, which causes particle buildup near the PRI drop and artificially affects the flow field (see Figure 5.9c). The particle stranding implies that the film thickness is closely related to the aspect ratio, although the PIV results for CG and RG3 are not obtained.

The forward and backward flows indicate unique characteristics of the film-wise transport, thus requiring further understanding. Knowing that the forward flow is generated by the capillary pressure difference, the lubrication approximation is used to model the forward flow. For thin-film flow on ribbon-like fibers, the longitudinal component of flow velocity  $u$  can be calculated using the classical Lubrication approximation by averaging the velocity along film thickness direction, as well as neglecting the inertial contribution, written as follows [53].

$$u = -\frac{h^2}{3\mu_w} \frac{dp}{dx} \quad (116)$$

The pressure gradient  $dp/dx$  consists of (a) the capillary pressure difference between the drop and the film and (b) the capillary pressure gradient along the film due to varying film thickness. Therefore, the pressure gradient can be calculated as follows.

$$\frac{dp}{dx} = \frac{\Delta p}{x} - \frac{\Delta p}{\lambda - x} + \gamma \frac{d\kappa}{dx} \quad (117)$$

where  $\Delta p$  is the film-drop pressure difference,  $\lambda$  is the PRI wavelength, and  $\kappa$  is the curvature of the water film.

For the forward flow, the last term in Eq.(117) vanishes because the major contribution is the film-drop pressure difference. The capillary pressure of PRI drop is  $2\gamma/r$ , where  $r$  is the equivalent radius of the PRI drop by curvature  $r = 2/(1/r_1 + 1/r_2)$ . The capillary pressure of film is  $\gamma(2h+2b)/a^2$ , because the liquid-vapor interface of the film is a circular arc sitting on an elliptical fiber. Therefore, the film-drop pressure difference is obtained as follows.

$$\Delta p = 2\gamma \left( \frac{h+b}{a^2} - \frac{1}{r} \right) \quad (118)$$

Therefore, the velocity of forward flow is calculated as

$$u_f = -\frac{2\gamma h^2}{3\mu_w} \left( \frac{h+b}{a^2} - \frac{1}{r} \right) \left( \frac{1}{x} - \frac{1}{\lambda - x} \right) \quad (119)$$

To solve Eq.(119), the film thickness  $h$  is calculated by applying mass conservation, where the water deposited on fiber equals the water transported to PRI drops. Therefore, the film thickness  $h$  from the edge of a PRI drop ( $x = r$ ) to the midpoint between two PRI drops ( $x = \lambda/2$ ) follows the below expression.

$$\frac{j\lambda}{2} = h(u_f|_{x=r} - u_f|_{x=\lambda/2}) \quad (120)$$

Substituting  $u_f$  with Eq.(119) gives

$$\frac{j\mu_w}{\gamma} = \frac{4}{3} \frac{h^3}{\lambda} \left( \frac{h+b}{a^2} - \frac{1}{r} \right) \left( \frac{1}{r} - \frac{1}{\lambda - r} \right) \quad (121)$$

Further simplification of Eq.(121) is possible because  $\lambda \gg r$ .

$$\frac{j\mu_w}{\gamma} = \frac{4}{3} \frac{h^3}{\lambda r} \left( \frac{h+b}{a^2} - \frac{1}{r} \right) \quad (122)$$

The characteristic length,  $a$ , and the characteristic velocity,  $\gamma/\mu$ , are used to cast the following non-dimensional parameters.

$$H = \frac{h}{a}; X = \frac{x}{a}; U = \frac{u\mu}{\gamma}; \Lambda = \frac{\lambda}{a}; \varepsilon = \frac{b}{a}; R = \frac{r}{a}; J = \frac{j\mu}{\gamma} \quad (123)$$

Then, Eqs. (119) and (122) are nondimensionalized as follows.

$$|U_f| = \frac{2H^2}{3} \left( H + \varepsilon - \frac{1}{R} \right) \left( \frac{1}{X} - \frac{1}{\Lambda - X} \right) \quad (124)$$

$$J = \frac{4H^3}{3\Lambda R} \left( H + \varepsilon - \frac{1}{R} \right) \quad (125)$$

Here,  $H$  is the film thickness on fiber belly. In Eq. (124),  $H+\varepsilon-1/R$  represents the contribution of capillary pressure difference due to the film curvature,  $2H+2\varepsilon$ , and the drop curvature,  $2/R$ ;  $1/X-1/(\Lambda-X)$  represents the contribution of the distance from film to two neighboring PRI drops. Together, the two terms indicate that two neighboring PRI drops compete for the deposited water over the distance of PRI wavelength. Moreover, at a fixed liquid flux  $J$ , a rounder ribbon-like fiber with a larger  $\varepsilon$  and smaller  $\Lambda$  has a smaller film thickness  $H$  compared to flatter fibers, explaining the particle stranding observed for fibers CG and RG3.

The model for forward flow is validated by the PIV results. As shown in Figure 5.10, the measured  $U_f$  for RG1 and RG2 agrees well with the theoretical model at  $X > 10$ , with  $R^2 \approx 0.68$  and  $0.91$ , respectively. The decreased  $U_f$  at larger  $X$  indicates a decrease in the net suction force due to a longer suction distance and the competing PRI drops. However, the measured  $U_f$  deviates from the model when approaching the PRI drop ( $X < 10$ ) due to film-drop transition. In the transition zone, the film thickness  $H$  increases to the scale of the PRI drop, which reduces  $U_f$  by providing a larger flow area. The value of  $U_f$  for RG1 and RG2 decreases to 40-60% of the peak value, indicating the film thickness of transition zone reaches  $H_t \approx 2H$ . Overall, the model explains the dynamics of forward flow at a sufficient distance from the PRI drop.

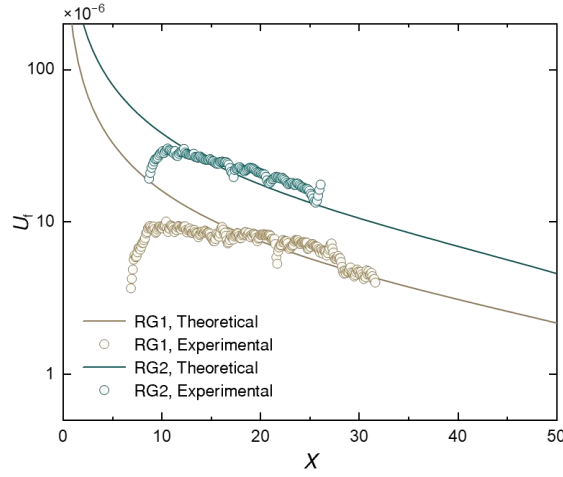


Figure 5.10. Plot of the dimensionless forward velocity,  $U_f$ , of RG1 and RG2 as a function of  $X$ .  $U_f$  obtained from the theoretical model and the experimental measurements by PIV are provided for comparison.

Figure 5.11a explains the formation of the backward flow. Due to the large suction force at adjacent distances, the shoulder film in the transition zone consistently squeezes the water into the PRI drop, forming an ultra-thin squeezing film (see Figure 5.11b). The small thickness of the squeezing film decreases the flow velocity due to  $u \propto h^2$ , which increases the Bernoulli pressure of the film by  $\Delta p \sim \rho \Delta(u^2)$ . The resulting adverse pressure gradient against the nearby forward flow develops a separation front near the boundary of the squeezing film, which reverses the direction of flow and provides mass source for the backward flow (see Figure 5.11c). Additionally, the loss of liquid mass on the fiber shoulder due to viscous entrainment into the forward flow leads to the thinning of the shoulder film. Consequently, the reduced capillary pressure due to film thinning builds a pressure gradient along the fiber axis, creating a reverse suction force to replenish the lost liquid mass. Essentially, the squeezing film cuts off the pressure “communication” between the film and the PRI drop, amplifying the reverse suction to drive the backward flow.

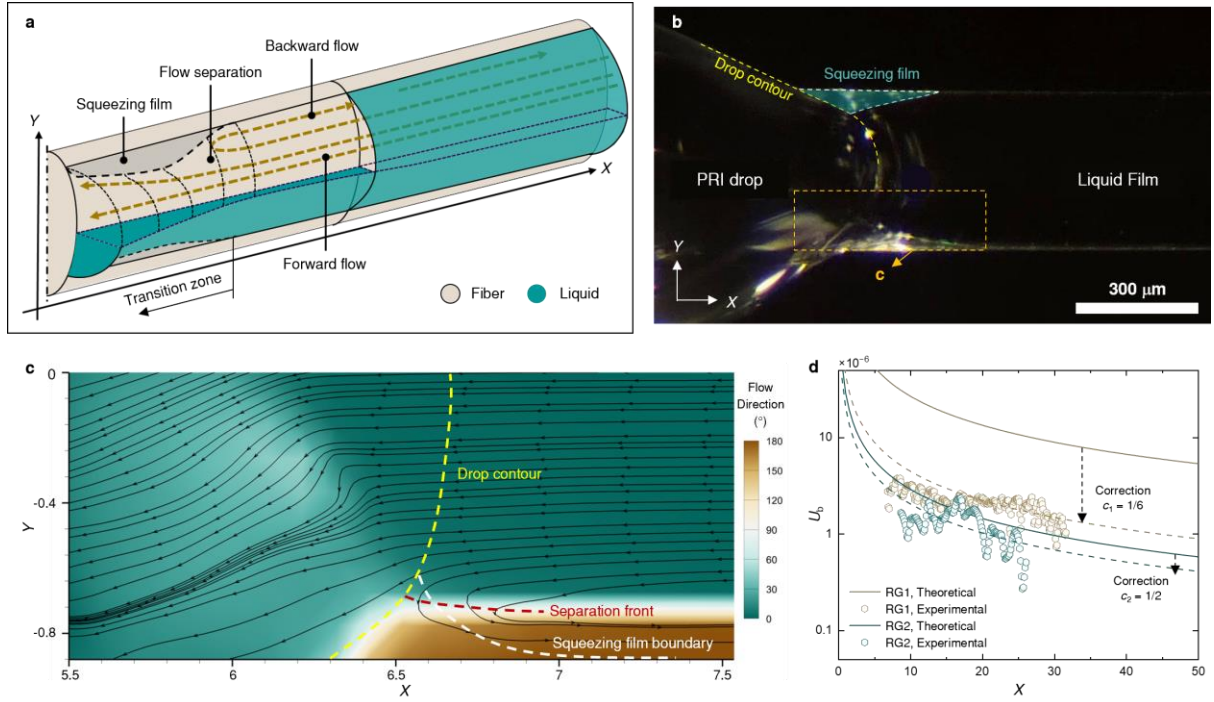


Figure 5.11. Explanation of the backward flow. (a) Schematic of formation of the backward flow. (b) Digital microscopic image of the squeezing film formed near fiber shoulder adjacent to the PRI drop. (c) PIV results of flow direction (contour) and streamlines (arrowed lines) for the film-wise flow in the region enclosed by orange dashed box in (b). (d) Plot of the dimensionless backward velocity,  $U_b$ , for RG1 and RG2 as a function of  $X$ .  $U_b$  obtained from the theoretical model and the experimental measurements by PIV are provided for comparison.

Similar to the forward flow, the backward flow is modeled based on the preceding mechanism. The term in Eq. (117) containing the film-drop pressure difference,  $\Delta p$ , vanishes due to the squeezing film. On the other hand, the gradient term exists to generate the reverse suction. Using the film curvature  $2H+2\varepsilon$ , the backward velocity can be calculated as follows.

$$U_b = -\frac{2H_b^2}{3} \frac{dH_b}{dX} \quad (126)$$

$H_b$  denotes the film thickness for the backward flow. For ribbon-like fibers with  $\varepsilon < 0.2$ ,  $H_b \approx H/2$  gives a good estimation based on an approximated film geometry (see Appendix C). In addition, the pressure gradient due to viscous entrainment can be scaled as  $dH/dX \sim H/X$ . Therefore, the backward velocity can be simplified as follows

$$|U_b| = \frac{H^3}{12X} \quad (127)$$

As shown in Figure 5.11d, the model predicts  $U_b$  with the same trend and order of magnitude as the PIV measured results. However, the model overestimates  $U_b$  because the scaling of pressure gradient overestimates the liquid loss due to viscous entrainment. Particularly, the

value of  $U_b$  for RG1 is more deviated compared to RG2, because the forward velocity  $U_f$  for RG1 is smaller compared to RG2, leading to less entrained liquid mass and larger overestimation. Introducing correction factors (RG1:  $c_1 = 1/6$ ; RG2:  $c_2 = 1/2$ ) to the scaled pressure gradient causes the experimental data to collapse on the model curves. Notably,  $c_1$  is 3 times smaller than  $c_2$ , which coincides with the ratio between the values of  $U_f$  for RG1 and RG2, implying a proportional relationship between the forward velocity and viscous entrainment. In addition, the measured  $U_b$  fluctuates, leading to small  $R^2$  of 0.58 and 0.14 for RG1 and RG2, respectively. The fluctuating backward velocity is caused by the vortices formed in the shear layer between the opposing flows, which is discussed later. Overall, the model explains the dynamics of backward flow and predicts the upper bound of  $U_b$ .

The models for the opposing flows allow further discussion of the characteristics of the film-wise transport. Eq. (125) indicates that, at a constant water flux  $J$ , the thickness  $H$  varies according to the aspect ratio  $\varepsilon$  and the PRI drop radius  $R$ . Specifically, for a flat ribbon-like fiber with small  $\varepsilon$ , the film thickness  $H$  increases to overwhelm the contribution of  $\varepsilon$ . Meanwhile, the term  $1/R$  usually vanishes because the drop radius,  $r$ , can grow much larger than  $a$  ( $R \gg 1$ ) due to the continuous transport. This useful scenario allows reducing the complicated form of Eq. (125) as follows.

$$H \approx \left(\frac{3}{4}JAR\right)^{\frac{1}{4}} \quad (128)$$

Therefore, Eq. (124) and (127) can be reduced to the form below.

$$U_f \approx 0.537(JAR)^{\frac{3}{4}} \left(\frac{1}{X} - \frac{1}{\Lambda - X}\right) \quad (129)$$

$$U_b \approx 0.067 \frac{(JAR)^{\frac{3}{4}}}{X} \quad (130)$$

Eq. (129) indicates a linear relationship between  $U_f$  and  $1/X$  when  $X \ll \Lambda - X$ , which is meaningful for long-wave PRI. Therefore,

$$U_f \approx 0.537 \frac{(JAR)^{\frac{3}{4}}}{X} \quad (131)$$

Eq. (130) and (131) and reveals two characteristics of the transport (a) both the forward and backward velocity scales with  $(JAR)^{3/4}/X$ , and (b) the forward velocity is 8 times greater than the upper bound of the backward velocity, thus governing the film-wise transport.

The preceding scaling relation of the forward flow can be generalized for practical situations. As shown in Figure 5.12, the forward velocity for RG2 varies linearly with  $(JAR)^{3/4}/X$  within the range of 2.5 – 5.5, indicating the scaling is robust for RG2. In contrast, the RG1 curve deviates from the scaling relation, because the PRI drop radius for RG1,  $R_A = 2.85$ , is insufficiently large to meet the criterion of  $R \gg 1$ . However, the growth of PRI drops is inevitable in long-term transport, therefore the scaling relation is robust for practical use. Using the scaling relation, the film-wise transport can be categorized into the transition phase, the linear phase, and the competing phase. The forward velocity in the transition phase negatively scales with  $(JAR)^{3/4}/X$  as  $U_f \propto -0.83(JAR)^{3/4}/X$  due to the film-drop transition. The competing phase is non-linear and finally reaches  $U_f = 0$  when  $X = A/2$  due to the rising contribution of  $1/(A-X)$  in Eq. (129). Clearly, the transport flowrate is determined by the linear phase as  $2U_f H = JAR/X$ . Therefore, the transport capacity can be improved in practical situations using ribbon-like fibers with long-wave PRI, where a long distance of linear phase satisfying  $X \ll A-X$  dominates the transport.

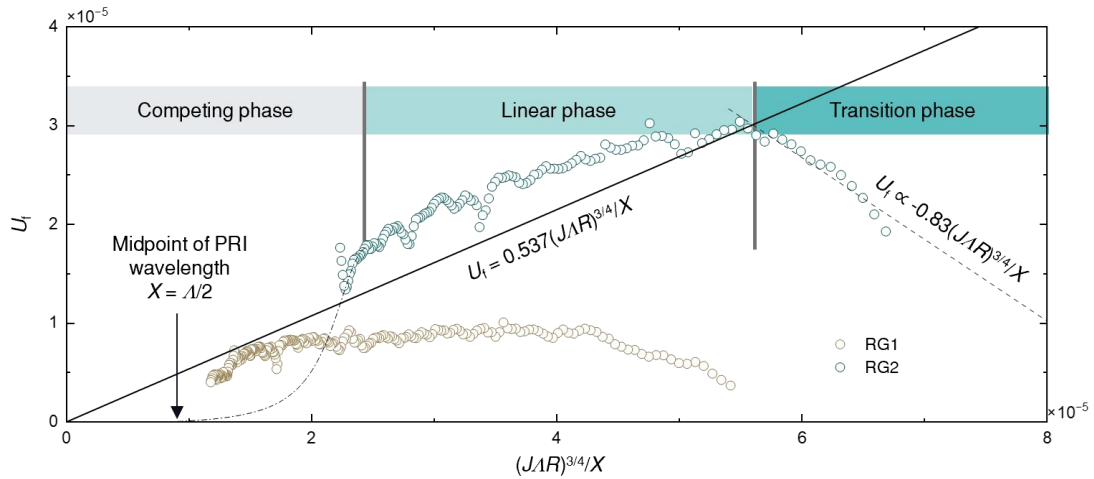


Figure 5.12. Plot of the scaling relation between  $U_f$  and  $(JAR)^{3/4}/X$  for three different phases of forward-flow transport.

Interestingly, a row of organized vortices is formed in the shear layer between the forward and backward flow due to Kelvin-Helmholtz instability (KHI). By zooming into a small region of RG1 containing the structure of the shear layer (see Figure 5.13a), seven organized elliptical vortices are captured rotating counter-clockwise with a maximum vorticity of  $6 \text{ s}^{-1}$ . The vortices are formed by KHI in the shear layer with a thickness of  $L_{sl} \approx 0.2$ , where small

perturbations grow to roll up the interface of velocity discontinuity, forming a row of vortices separated by the distance of the dominating KHI wavelength. Using linear stability analysis [249], the wavelength can be predicted as  $\lambda_{KHI} \approx 2.5\pi L_{sl} = 1.57$ . However, by correlating the number of vortex cores to their  $X$  coordinates (see Figure 5.13b), the measured inter-vortex spacing is averaged as 0.45, which is 71% smaller than the theoretical KHI wavelength. This deviation may be caused by the non-linear development of KHI, where sub-harmonics develop to reduce the wavelength [250]. The micrometer-scale size of the vortices implies that the shear-induced vortices may enhance the mixing of the film-wise flow.

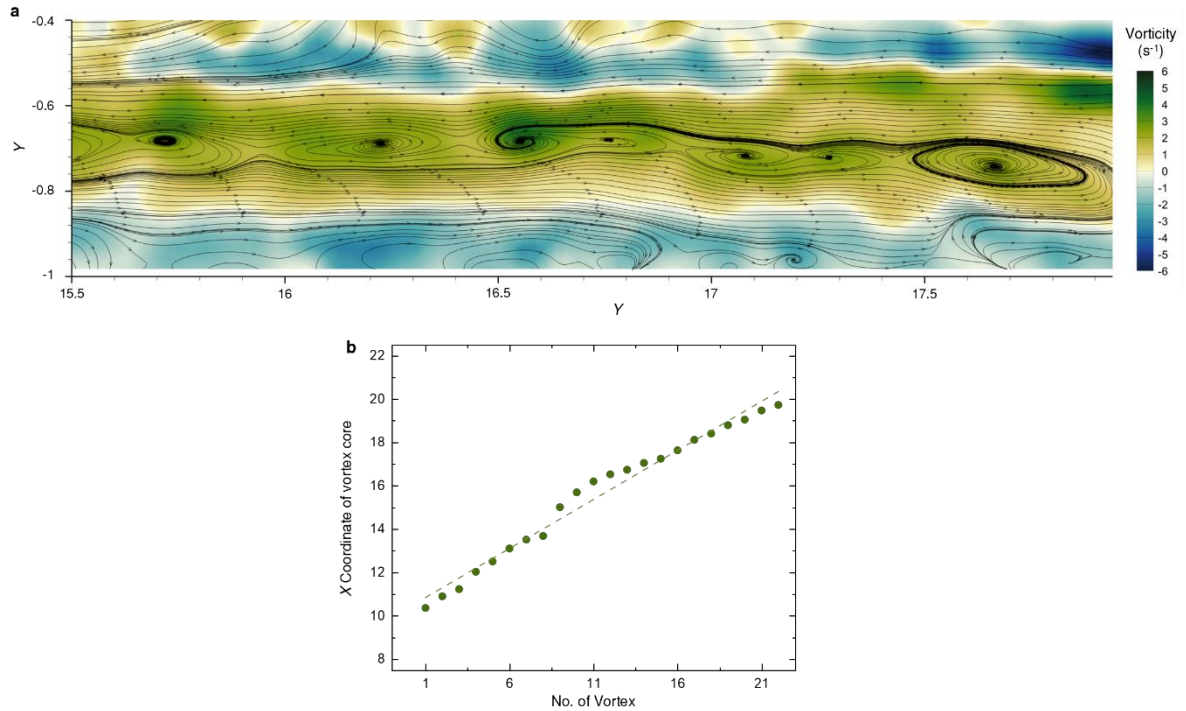


Figure 5.13. Vortices formed by KHI in the shear layer. (a) PIV result of the vorticity (contour) and streamlines (arrowed lines) for the shear layer between the forward and backward flow. (b) Plot of  $X$  coordinates of shear-induced vortex cores as a function of number of vortices. The dashed line in (b) is the best linear fitting with a slope of 0.45.

### 5.3.3 Continuous water transport on rivulets-on-web structures

A single ribbon-like fiber has the intriguing ability of spontaneous and continuous water transport. However, practical applications normally involve fiber networks to increase surface area or enhance mechanical strength. For the fiber network, the intersection of fibers provides a lower-energy surface, inducing the formation of waterdrops. Knowing that the drops disrupt continuous transport, a network structure is required to transport water without drop formation.

This study designs a rivulets-on-web (ROW) structure to continuously transport water without forming drops at fiber intersections. As shown in Figure 5.14, a web consisting of

vertical and horizontal fibers are weaved by creating a fiber spacing described below. Specifically, the horizontal fibers are ribbon-like to eliminate the formation of PRI drops over the spacing  $l_1 < \lambda$  due to their long-wave PRI. The vertical fibers are arranged in such a way that the deposited water between the two close fibers separated by  $l_2$  can form a stable water bridge, whereas the two distant fibers separated by the spacing  $l_1 - l_2$  cannot hold a stable bridge. This arrangement essentially uses the stable water bridge as an artificial PRI “drop”. As a result, the ribbon-like fibers can spontaneously transport the deposited water as a “branch rivulet” into the water bridge, which further transports the water as a “main rivulet”.

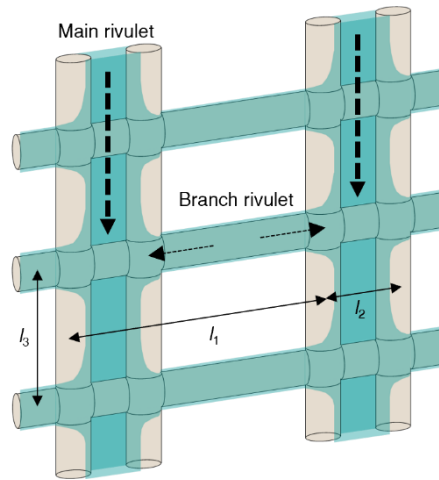


Figure 5.14. Schematic of conceptual design for ROW structure.

Based on the conceptual design, four fiber webs (W1 – W4) are fabricated using near-field electrospinning and fixed with two copper gaskets as the web frame, which is similar to the assembled fog collector presented in Chapter 4. The fiber web with an area of  $10 \text{ cm}^2$  consists of PVDF-HFP ribbon-like fibers with  $a = 40 \text{ }\mu\text{m}$  and  $\varepsilon = 0.14$ . In addition, the spacing  $l_1$  is controlled within the range of  $2 \text{ mm} - 4 \text{ mm}$ , because the dominating PRI wavelength for the fiber is in the range of  $1.3 \text{ mm}$  (wrapping film) –  $6 \text{ mm}$  (ridge film). Also, two different  $l_2$  of  $0.2 \text{ mm}$  and  $0.5 \text{ mm}$  are used to investigate the influence of main rivulet width on the ROW structure. Furthermore,  $l_3$  is kept constant as  $0.5 \text{ mm}$  because it imposes negligible effect on ROW structure other than the stability of the water bridge, which is beyond the scope of this study. The detailed parameters for fiber webs are listed in Table 5.1.

Table 5.1. Geometrical parameters for the fabricated fiber webs

|    | $a \text{ (}\mu\text{m)}$ | $\varepsilon$ | $l_1 \text{ (mm)}$ | $l_2 \text{ (mm)}$ | $l_3 \text{ (mm)}$ |
|----|---------------------------|---------------|--------------------|--------------------|--------------------|
| W1 | 40                        | 0.14          | 2                  | 0.5                | 0.5                |

|    |  |  |   |     |     |
|----|--|--|---|-----|-----|
| W2 |  |  | 3 | 0.5 | 0.5 |
| W3 |  |  | 4 | 0.5 | 0.5 |
| W4 |  |  | 3 | 0.2 | 0.5 |

The fabricated fiber webs are exposed to water deposition at fluxes,  $j$ , of  $4 \mu\text{m s}^{-1}$ ,  $14 \mu\text{m s}^{-1}$  and  $37 \mu\text{m s}^{-1}$  for the formation of ROW structure. Within 30 minutes of exposure, the tested webs are covered with water bridges with different structures (see Figure 5.15). For W1, the deposited water overwhelms the spacing  $l_1$  at the lowest flux ( $j = 4 \mu\text{m s}^{-1}$ ), spreading the bridge across the whole fiber web. In contrast, W2 can isolate the bridge into vertical main rivulets while preventing the formation of any PRI drops even at the maximum flux ( $j = 37 \mu\text{m s}^{-1}$ ), indicating a successful ROW structure. In addition, W3 can also isolate the water bridge; however, the formation of PRI drops is observed between the main rivulets at  $j = 37 \mu\text{m s}^{-1}$ . Furthermore, W4 with a smaller  $l_2 = 0.2 \text{ mm}$  shows a similar phenomenon as W3, because the narrow main rivulets cannot provide sufficient suction force on branch rivulets as an artificial PRI drop, triggering PRI on horizontal fibers. Upon the formation of ROW structure, W2 can continuously transport water for the entire period of a 3-hour test without forming any drops at the maximum flux of  $37 \mu\text{m s}^{-1}$ .

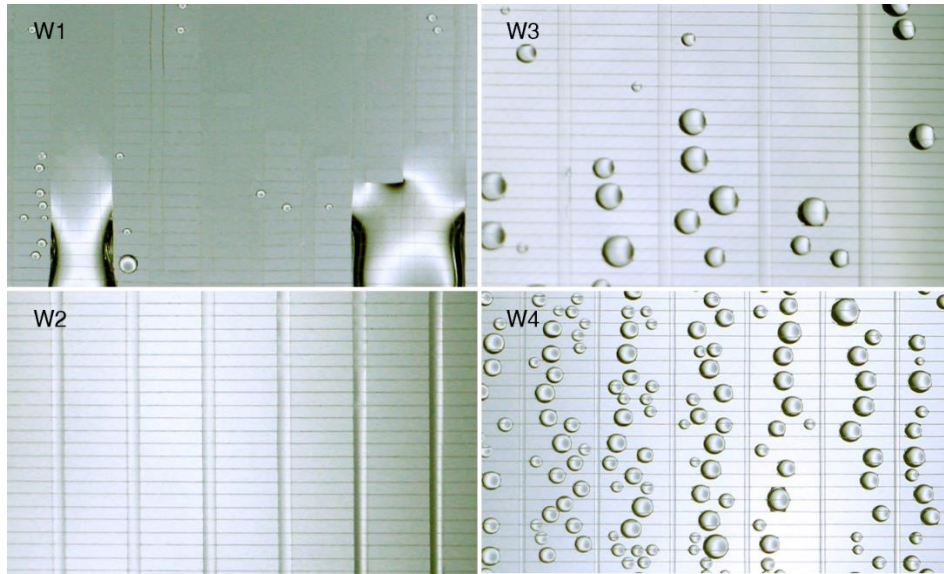


Figure 5.15. Digital image of four different fiber webs (W1-W4) exposed to water deposition at a flux of  $37 \mu\text{m s}^{-1}$  for 30 minutes.

To understand the transport characteristics of the ROW structure, the flow in the main rivulets of W2 is visualized using trace particles. At a water flux of  $j = 4 \mu\text{m s}^{-1}$ , the trajectory of trace particles (see Figure 5.16a) indicates that the water flows downward near the centerline of the main rivulet, and the downward flow is flanked by a pair of counter-rotating vortices

bounded by each mesh. The PIV analysis (see Figure 5.16b) shows that the downward velocity reaches a maximum of  $2.4 \text{ mm s}^{-1}$  at the center of the mesh. In addition, at a higher water flux of  $j = 37 \text{ } \mu\text{m s}^{-1}$ , the maximum velocity increases to about  $3.8 \text{ mm s}^{-1}$ , which however cannot be accurately measured by PIV because of the foggy field of view. It is reasonably speculated that the thickness of main rivulet increases 5.8 times to transport more water, because the velocity increases only 1.6 times when the deposited water flux increases 9.25 times.

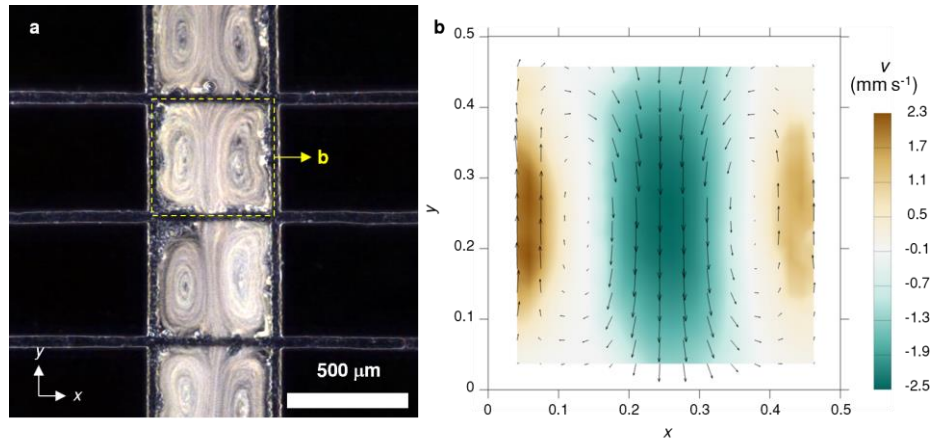


Figure 5.16. Liquid transport in the main rivulet of ROW structures. (a) Digital image of particle trajectory in the main rivulet. The trajectory image is obtained by time projection of a 500-frame video. (b), PIV results of vertical component of velocity (contour) and velocity vector (arrow) for the main rivulet in the region enclosed by yellow dashed box in (a).

The downward flow is driven by the capillary pressure gradient along the main rivulet, which results from the difference in the curvature of the liquid-vapor interface. As shown in Figure 5.17, the liquid-vapor interface between two fibers has a positive curvature due to surface tension, leading to a capillary pressure larger than the ambient pressure; however, the interface is flattened when the water spreads on the wettable web frame, thus lowering the pressure to about 1 atm. As a result, the pressure gradient drives the water in the main rivulet flowing downward to the web frame. In addition, the formation of vortices is due to the constrained flow past the horizontal fiber. The positive curvature of the liquid-vapor interface leads to a thick film near the centerline of the main rivulet, allowing the downward flow to circumvent the horizontal fiber. Conversely, the film near the rivulet edge becomes sufficiently thin so that the horizontal fiber obstructs the downward flow, resulting in flow separation and recirculation. Overall, the ROW structure can transport water to wettable surfaces within a certain range of water flow rates by adjusting the thickness of the main rivulets, while simultaneously forming symmetric vortex structures along the transport path.

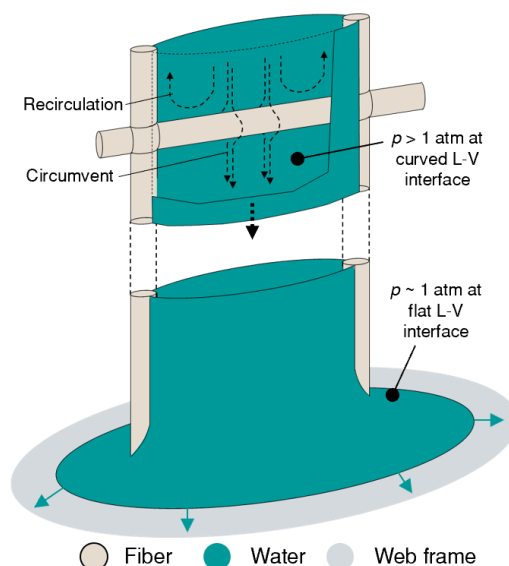


Figure 5.17. Schematic of the capillary pressure gradient and vortex formation in the main rivulet.

## 5.4 Summary

This work reports the spontaneous and continuous water transport leveraging long-wave PRI of ribbon-like fibers. The deposited water aggregates on the belly of ribbon-like fibers and triggers long-wave PRI due to the slightly curved surface of the fiber belly. After PRI occurs, the precursor film connecting neighboring PRI drops is thickened by the deposited water and transports the water to the nearest drop. A pair of opposing flows are formed during the film-wise transport due to the capillary pressure difference and water film shape. The velocity of the opposing flows scales with the flux of deposited water, PRI wavelength and PRI drop radius and theoretically differs by 8 times. The opposing flows induce non-linear Kelvin-Helmholtz instability to roll up vortices within the shear layer, therefore enhancing the flow mixing. Owing to the long-wave PRI, a rivulets-on-web structure is demonstrated to continuously transport water over a 10 cm<sup>2</sup> fiber network without the formation of any drops that hinder the transport.

The continuous and spontaneous water transport on ribbon-like fibers and the ROW structure have broad applications in thermal, chemical and environmental technologies. For example, continuous film-wise transport can accelerate the renewing of liquid-vapor interface, which may reduce the local level of temperature or chemical species, thus increasing the driving force for heat and mass transfer. In addition, the flow mixing based on the shear-induced vortices can further agitate the transport phenomena at micrometer level without external inputs of mechanical energy. Furthermore, the suppressed formation of PRI drops on ROW structure can improve the aerodynamic characteristics of fibrous media in terms of

reducing pressure drop and droplet entrainment. Overall, the enhanced mass and heat transfer and the improved aerodynamic characteristics may offer promising prospects for technologies such as condensers, gas absorbers and water harvesting.

## Chapter 6 Conclusions and Future Works

### 6.1 Conclusions

This thesis investigates the droplet capture and water transport on thin fibers and evaluates the collection efficiency on fiber-based collectors. First, a multi-scale numerical model is developed to investigate fog water collection efficiency for thin-fiber grids. The fog harvesting process is modeled at two scales, i.e., collector scale and fiber scale, and the two scales are coupled together through pressure loss coefficient and ratio of captured water droplets. The result reveals two important effects on collection efficiency – the wall effect and positive clogging effect. The wall effect increases pressure loss in the dense thin-fiber grid due to the interaction of thick boundary layers, leading to a reduced penetrating airflow and overall efficiency. The positive clogging enhances droplet capture capability of the sparse thin-fiber grids by providing a larger projected area. The studied effects are mapped according to the geometry of fiber grids, which provides new insights into the geometrical design and drainage capability of novel fog collectors. The results extend the current theories of fog harvesting by introducing the wall effect and positive clogging effect and provide guidelines for fiber-based fog collector design.

Then, this thesis investigates the effects of waterdrop clogging on fog water collection using micro-fiber grids. The experimental study shows that small waterdrops are “visible” to incoming airflow because of the thin fiber diameter, therefore effectively capturing the fog droplets. On the other hand, a numerical simulation evidences that the growth of waterdrops forms a pattern that deflects the airflow from large waterdrops to the satellite small ones, enhancing the fog capture on small waterdrops at low air velocity. Based on the enhanced droplet capture, fog collectors consisting of micro-fiber grids are fabricated, exhibiting an outstanding collection efficiency of 21.4%. The fabrication requires an exceedingly low amount of inexpensive polymers without creating complex surface structures or chemical treatment, showing immense potential to collect fog water. Moreover, the micro-fiber based collector provides an effective strategy to increase the water collection efficiency - reducing the diameter of the solid structure to let waterdrops directly capture fog droplets.

Finally, this thesis discovers the spontaneous and continuous water transport leveraging long-wave PRI of ribbon-like fibers. Experiments and theoretical analysis indicate that the deposited water on fibers aggregates on the belly of ribbon-like fibers and triggers long-wave

PRI due to the slightly curved surface of the fiber belly. After PRI occurs, the precursor film connecting neighboring PRI drops is thickened by the deposited water and transports the water to the nearest drop. Flow visualization and PIV analysis reveal that a pair of opposing flows are formed during the film-wise transport due to the capillary pressure difference and water film shape. The velocity of the opposing flows scales with the flux of deposited water, PRI wavelength and PRI drop radius and theoretically differs by 8 times. The opposing flows induce non-linear Kelvin-Helmholtz instability to roll up vortices within the shear layer, therefore enhancing the flow mixing. Owing to the long-wave PRI, a rivulets-on-web structure is demonstrated to continuously transport water over a 10 cm<sup>2</sup> fiber network without the formation of any drops that hinder the transport.

## 6.2 Recommended future works

The following recommendations are suggested for future research works based on the study in this thesis.

- (1) **Improving the mechanical strength of the micro-fiber grids.** Future improvements in terms of mechanical strength of micro-fiber grid are expected to harvest more water from fog laden wind with high speed. Currently, the tensile strength of the PVDF-HFP micro-fiber grid fabricated by NFES is ~20 times lower than the dense PVDF-HFP fiber membrane fabricated by conventional electrospinning [204], as a result of sparse distribution and ultrafine thickness of fibers. To apply micro-fiber grid collectors in wind >5 m s<sup>-1</sup>, durable materials with high intrinsic strength, such as metallic or ceramic fibers, should be explored to resist the drag of airflow.
- (2) **Controlling the size of clogging waterdrops.** The results in Chapter 3 and Chapter 4 indicates that the clogging drops can be beneficial to collection efficiency on micro-fiber grids. However, controlling clogging drop sizes is essential for the positive clogging effect, where large clogging drops that connect multiple grid openings should be avoided. The control of clogging drops requires further studies to understand the mechanism of waterdrop growth and shedding on micro-fibers, which normally depend on the surface wettability of the collector and should be studied in the future.
- (3) **Investigating droplet re-entrainment during fog harvesting.** The loss of collection efficiency due to re-entrainment, i.e.,  $\eta_{dr}$ , is neglected throughout this thesis due to the low velocity of airflow. However, the re-entrainment of droplets is relatively important for a high velocity fog flow and sparse fiber grids, where the air drag overcomes the

adhesion between the collector and the drops. This scenario is particularly important for the application of micro-fiber grids for industrial fog harvesting, because the industrial gases in cooling towers and stacks usually have large velocities, thus requiring further investigations.

- (4) **Scaling up the fabrication process of NFES.** Fog collectors used to harvest atmospheric fog and cooling tower plume generally requires a large size scale in meter level. The collectors fabricated in the present study are limited to a centimeter scale due to the lab-size NFES system. Therefore, scaling up the NFES system with multiple spinnerets [97, 206] is required for fabricating micro-fiber collectors for practical use. In addition, other scalable techniques that can produce micro-fiber grids in large scale should be further studied and developed as future works.
- (5) **Application of liquid transport on ribbon-like fiber in other areas.** The ribbon-like fibers can continuously transport deposited water over a centimeter-level distance while generating shear-induced vortices to enhance flow mixing. These unique characteristics of liquid transport can inspire applications in areas other than fog harvesting, such as mass and heat transfer. Therefore, the transport phenomenon on ribbon-like fibers should be further investigated by introducing other processes, such as condensation and physical/chemical absorption, and liquid with different viscosity and surface tension.

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## Appendix A Parameters for Model Validation

### A1. Parameters for validating the close-up model

The close-up model is validated using experiment results reported by Labbé et al for fog droplets deposited on wet vertical fibers [1]. The parameters are extracted from the literature and provided in Table A1.

Table A1 Parameters used for validating the close-up model

| Parameter    | Unit              | 1       | 2   | 3   | 4    |
|--------------|-------------------|---------|-----|-----|------|
| $d_{fiber}$  | $\mu\text{m}$     | 85      | 300 | 600 | 800  |
| $u_p$        | $\text{m s}^{-1}$ | 0.5~3.5 |     |     |      |
| $d_{fog}$    | $\mu\text{m}$     | 6       |     |     |      |
| $l_{sp}$     | $\text{mm}$       | 1.5     |     |     |      |
| $r_c$        | $\text{mm}$       | 0.3     | 0.5 | 0.7 | 0.75 |
| Drop spacing | $\text{mm}$       | 2       | 4   | 4   | 4    |

### A2. Parameters for validating the full-size model

The full-size model is validated using experiment results reported by Park et al. [12], Kowalski et al. [80], and Huang et al. [78]. Indeed, the calculation of full-size model also requires the inputs of respective close-up model with specific geometries of fiber grid and water clogging. Therefore, the validation of the full-size model is carried out along with the corresponding close-up model. All parameters used in two models are extracted from the literature and provided in Table A2.

Table A2 Parameters used for validating the full-size model.

| Parameter   | Unit              | R    | H1        | H2        | MF1 | MF2 | MF3 |
|-------------|-------------------|------|-----------|-----------|-----|-----|-----|
| $d_{fiber}$ | $\mu\text{m}$     | 1200 | 254       | 254       | 10  | 10  | 10  |
| $u_0$       | $\text{m s}^{-1}$ | 2    | 1.4       | 1.4       | 1.8 | 1.8 | 1.8 |
| $d_{fog}$   | $\mu\text{m}$     | 7    | 18        | 18        | 16  | 16  | 16  |
| $l_{sp}$    | $\text{mm}$       | 6    | 1.016     | 0.508     | 0.2 | 0.3 | 0.4 |
| $r_c$       | $\text{mm}$       | 0*   | 0.1~0.5** | 0.1~0.5** | *** | *** | *** |

|              |    |      |       |       |      |      |      |
|--------------|----|------|-------|-------|------|------|------|
| Drop spacing | mm | N/A* | 1.5** | 1.5** | ***  | ***  | ***  |
| $L_d$        | mm | 60   | 86    | 86    | 36.8 | 36.8 | 36.8 |

\* No clogging on Raschel mesh is reported in Ref. [12].

\*\* Values are obtained by measuring drop radius and spacing in the digital photos provided in Ref. [80]. The final collection efficiency is calculated by averaging the results of different  $R_c$ .

\*\*\* Polydisperse drop radius and spacings are used for modelling. See below explanations and sampling methods.

Specifically, the polydisperse radius and spacings of clogging drops on micro-fiber grids (MF1-3) are modeled to accurately predict the collection efficiency, because Chapter 4 points out that the difference in waterdrop radius and spacing can influence the overall efficiency through the variation of local flow field. The drop size and number obtained from Chapter 4 are logarithmically sampled to yield a drop size spectrum consisting of six polydisperse radii, because the radius follows a power-law distribution. Six sampling radii can sufficiently represent the polydisperse clogging size within a minimal domain in close-up model. On the other hand, the spacing between clogging drops is controlled by the following principle to better interpret the actual clogging situation described in Chapter 4: (a) the clogging drops are primarily placed on the interception of fibers; (b) The large clogging drops are placed far from each other; the gaps between larger drops are filled with smaller ones; (c) the small drops can reside on fibers instead of fiber interceptions if all the interceptions are occupied. Figure A1 shows the comparison between the model and actual clogging situation for MF2.

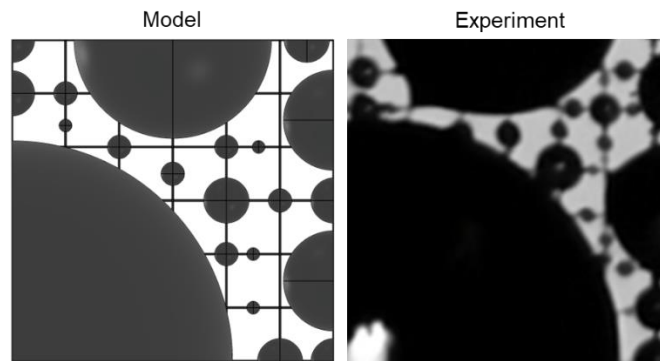


Figure A1. Comparison between modeled and actual micro-fiber grid MF2

## Appendix B NFES Trajectory Programming

### B1. General description

The trajectory of NFES is programmed to control fiber patterning. Specifically, the code commands the X-Y stage to conduct reciprocal motions for a displacement of  $L$  along Y axis, while stepping forward for a displacement of  $l_{sp}$  along the X axis each time the stage reaches one end of the Y direction. This allows NFES to deposit parallel microfibers. Afterwards, the sequence of motion along X and Y direction is exchanged to deposit parallel fibers that are perpendicular to the existing fibers. As a result, grid patterns are created with controlled fiber spacing of  $l_{sp}$ . Moreover, the diameter of the fibers can be controlled by adjusting the speed of the reciprocal motion; faster motion stretches the jet and forms thinner fibers, while the slower one is thicker.

### B2. Programming method

The programming of NFES trajectory is carried out by following the process diagram given in Figure B1. The program starts with checking and homing the position of the stage. The sensor of stage positioner gives the coordinate of the positioner as  $X$  and  $Y$ , which is compared to the origin (0,0). If the positioner deviates from the origin, the stage is commanded to move to the origin, and repeat the checking and homing steps. Otherwise, the stage is homed and ready for executing trajectorial movements. Then, the stage is moved to  $(-L/2, -L/2)$  as the startup position for trajectory, where  $L$  is obtained from program input. Once the position is reached, a loop command is executed to move the stage along the designed trajectory. The program first reads the coordinate  $X$ ; if  $X < 0$ , the stage is translated along the  $X$  direction for a distance of  $L$  by increasing  $X$ , and vice versa. When completing the translation, the stage is then translated along the  $Y$  direction for a distance of  $l_{sp}$  by increasing  $Y$ . The iteration of translation on  $X$  and  $Y$  direction continues until  $Y$  is larger than  $L$ . Finally, the discontinued loop leads to the end of the program execution.

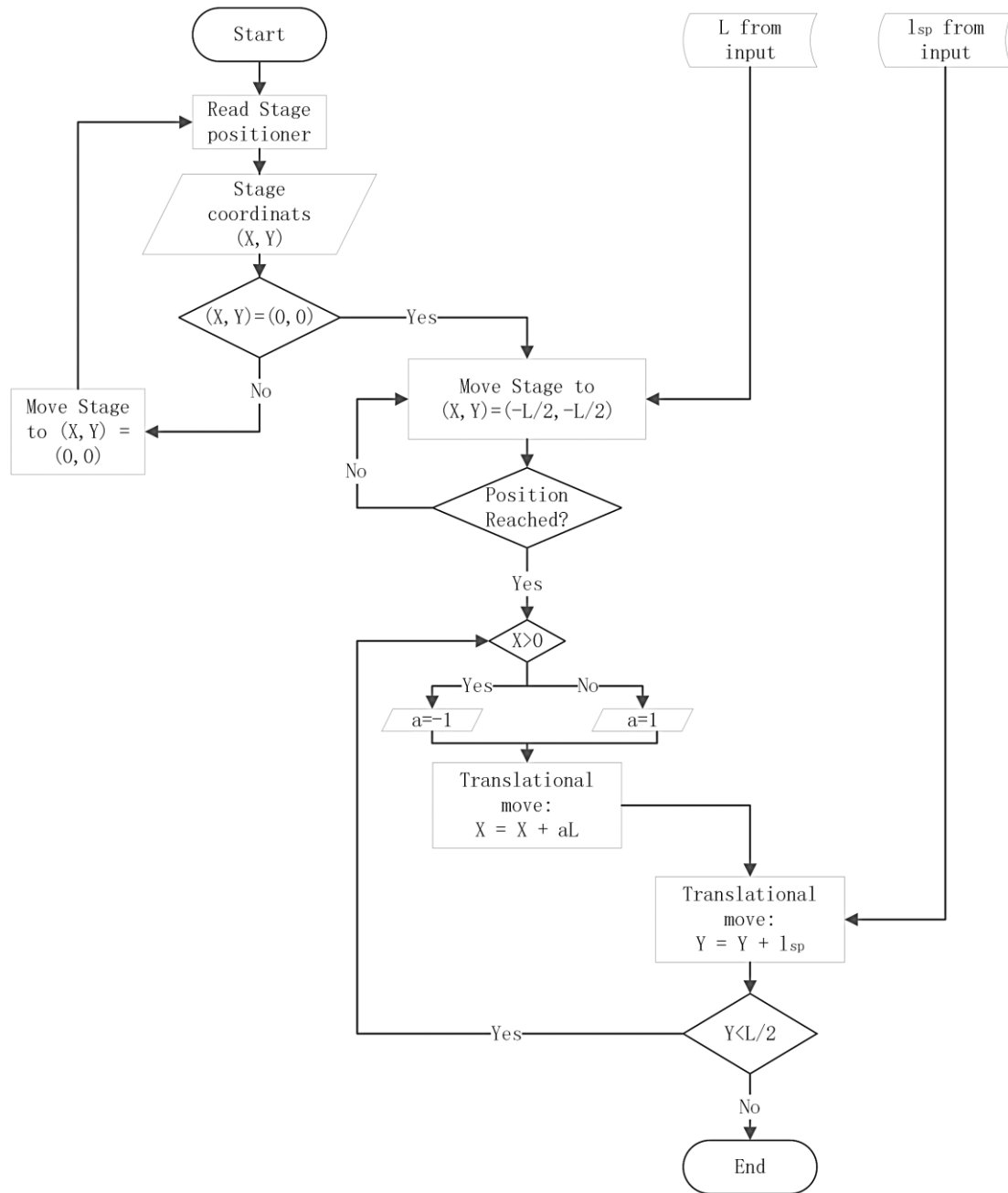


Figure B1. Process diagram for the program of NFES trajectory

The coding of the preceding program is realized in LabView software (NI, USA) along with the commands for camera and controller communication for NFES system. The codes of program commands are modularized and invoked in an integrated user interface. Together, all codes are compiled and packed into an executable program to interface with the NFES system. The modularized codes are provided in <https://github.com/hyq7619878/NFES-trajectory.git>.

## Appendix C Approximation of Water Film Geometry

Figure C1a shows that the water film on a ribbon-like fiber with a major radius of  $a$  and minor radius of  $b$  has a cross-section shape of a circular area sitting on an ellipse. The bulging surface of the film leads to a larger belly film thickness of  $h$ , where the forward flow takes place, and a thinner film thickness of  $h_b$ , where the backward flow occurs. As discussed in Chapter 5, the distance between  $h$  and  $h_b$  is about  $0.7a$ . However, the combination of circular and ellipse shape leads to a rather complex mathematical relationship between  $h$  and  $h_b$ , which is difficult to interpret physically.

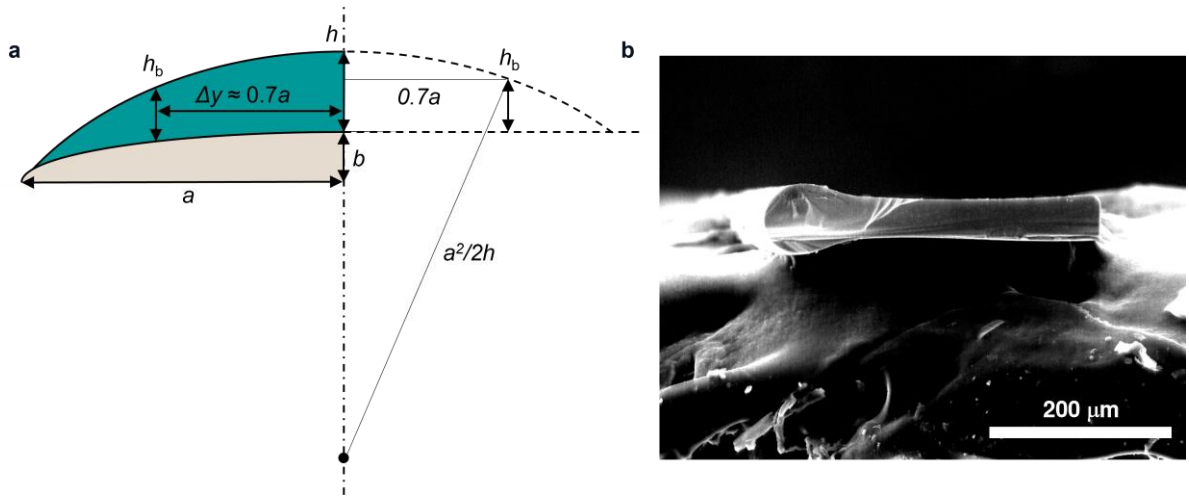


Figure C1. (a) Schematic of approximated water film geometry. (b) Scanning electron microscope image of the cross-section of a ribbon-like glass fiber with  $\varepsilon = 0.2$ .

Here, the geometry of the water film is approximated for better physical interpretation. Considering that  $b \ll a$  for the tested ribbon-like fibers RG1 and RG2 with  $\varepsilon < 0.2$ , the bulging surface of the ellipse is quite flat and can be approximated as a planar surface (dash line in Figure C1a). This approximation is practically reasonable because the ribbon-like fiber with a small  $\varepsilon$  used in this study usually adopts a flatter cross section (see Figure C1b) compared to a regular ellipse. The planar surface directly simplifies the film geometry as a circular cap sitting on a plane, which leads to the following relationship between  $h_b$  and  $h$ .

$$\frac{h_b}{h} = 1 - \left( \frac{a^2}{2h^2} - \frac{a}{h} \sqrt{\frac{a^2}{4h^2} - 0.49} \right) \quad (132)$$

The expression has a non-dimensional form as follows.

$$\frac{H_b}{H} = 1 - \left( \frac{1}{2H^2} - \frac{1}{H} \sqrt{\frac{1}{4H^2} - 0.49} \right) \quad (133)$$

Eq. (133) indicates  $H_b/H$  is in the range of 0.49-0.51 for  $0 < H < 0.3$ , which covers the range of  $H$  in this study calculated by Eq. (125). Therefore, the approximation provides a good estimation of  $H_b$  as follows.

$$H_b = 0.5H \quad (134)$$