ADVANCED FUNCTIONAL MATERIALS
www.afm-journal.de

Magnetically Induced Fog Harvesting via Flexible Conical Arrays

Yun Peng, Yaxu He, Shuai Yang, Shuang Ben, Moyuan Cao, Kan Li, Kesong Liu, and Lei Jiang*

Water is the driving force of all nature. Securing freshwater has been one of the most important issues throughout human history, and will be important in the future, especially in the next decade. Fog is ubiquitous in nature and is therefore considered as an alternative and sustainable freshwater resource. Nature has long served as a source of inspiration to develop new fog-harvesting technologies. However, the collection of freshwater from static fog is still a challenge for the existing bio-inspired fog-harvesting systems. Herein, magnetically induced fog harvesting under windless conditions through the integration of cactus-inspired spine structures and magnetically responsive flexible conical arrays is reported. Under an external magnetic field, static fog can be spontaneously and continuously captured and transported from the tip to the base of the spine due to the Laplace pressure difference. This work demonstrates the advantage of collecting fog water, especially in windless regions, which provides a new avenue for fog harvesting and can serve as a source of inspiration to further optimizations of existing fog-water-harvesting strategies.

1. Introduction

All organisms, including human beings, require water for their survival. Although water is the most widespread resource to be found in the natural environment, freshwater, the essential substance for humans, constitutes only about 2.5% of the total volume of water on earth.[1] Furthermore, in the next decade, freshwater shortages and scarcity may be one of the main global threats. In the Global Risks report, the water crisis was categorized as an environmental risk in 2014 but as a societal risk in 2015. The World Economic Forum also reported that two-thirds of the world population will be experiencing water stress conditions by 2025.[2]

Securing freshwater—to drink, to bathe in, to irrigate crops—is an important issue as old as civilization. Fog, as an alternative source of freshwater, has attracted increasing attention arising from its large density of small water droplets.[3] In nature, some biological materials, such as desert beetles, namib grass, cactus, and *Cotula fallax* plants, have evolved optimized and smart structures to collect freshwater from fog-laden wind for their survival.[4] Inspired by these biological materials, many different synthesis strategies have been developed to construct bio-inspired materials with fog-collecting abilities.[5]

The fog-harvesting efficiency not only depends on the fog droplet diameter and the fog-collecting surface nature, but also depends on the fog-laden wind speed.[6] Fog-harvesting organisms and bio-inspired fog collectors exhibited their effectiveness under a natural fog-laden wind or an artificial fog flow with a certain speed, demonstrating passive fog-collecting. However, in some foggy regions, fog with low flow ability can halt on the ground and air, which will significantly reduce the fog-harvesting efficiency for the current fog collectors.[7] Therefore, harvesting fog water in an almost static atmosphere is still a challenge for the existing fog-collecting strategies.

Herein, through the integration of cactus spine-like structures and magnetically responsive flexible conical arrays, we report magnetically induced fog harvesting in an airtight chamber filled with a quasistatic mist of water. Under the magnetic field, static fog can be spontaneously and continuously captured accompanying durative vibrations of magnetic-driven conical needles. Furthermore, the shape gradient-induced Laplace pressure difference is beneficial to the water droplets transportation. This work presents the advantage of harvesting fog water under windless conditions, which may serve as a source of inspiration for scientists and engineers to further improve the existing fog-collecting strategies. Learning from nature is a promising avenue for collecting fog water as an alternative and sustainable freshwater resource.

Dr. Y. Peng, Y. He, Dr. S. Yang, S. Ben,
Dr. M. Cao, Prof. K. Liu, Prof. L. Jiang
Key Laboratory of Bio-Inspired Smart Interfacial
Science and Technology of Ministry of Education
Beijing Key Laboratory of Bio-Inspired Energy
Materials and Devices
School of Chemistry and Environment
Beihang University
Beijing 100191, P. R. China
E-mail: liuks@buaa.edu.cn
Dr. K. Li, Prof. L. Jiang
Laboratory of Bio-Inspired Smart Interface Science
Technical Institute of Physics and Chemistry
Chinese Academy of Sciences
Beijing 100190, P. R. China

DOI: 10.1002/adfm.201502745

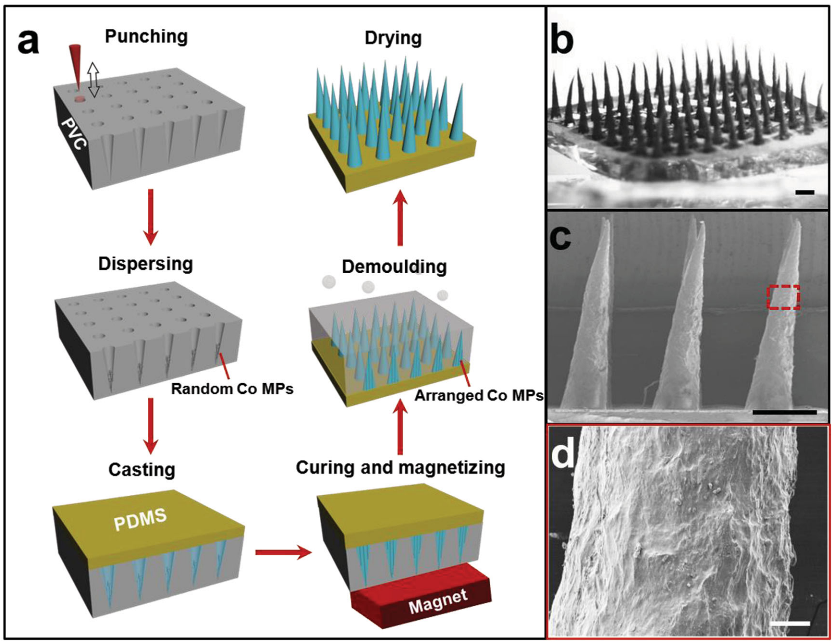

Figure 1. Schematic for the fabrication of cactus-inspired ordered magnetically conical arrays and the corresponding optical and SEM images. a) The fabrication procedure of the magnetically conical array. b) Optical photograph and c) SEM image of the orderly and squarely arranged magnetically conical array on a nonmagnetic backing layer. d) Magnified SEM image of the middle part of a magnetic cone. The height of the regular magnetic cones, the diameter of the cones at base, and the separation between the adjacent cones at base are approximately 3 mm, 770 μm, and 680 μm, respectively. Scale bars: b,c) 1 mm; d) 50 μm.

2. Results and Discussion

Figure 1a shows a schematic diagram for the fabrication of cactus-inspired ordered magnetically conical arrays. The preparation steps are explained in detail in the Experimental Section. Cactus spine-like magnetic arrays were fabricated using the polydimethylsiloxane (PDMS) prepolymer and cobalt magnetic particles (Co MPs) through a facile approach combining the mechanical punching and the template dissolving technology.[8] In comparison with the conventional template removal technology,[5e,8] the template dissolving method exhibited more versatility to achieve a well-defined magnetically conical array. The optical photograph and scanning electron microscope (SEM) image (Figure 1b,c) clearly demonstrate that the magnetically conical arrays possess micro/nano multiscale surface structures (Figure 1d). The height of the resultant regular magnetic cones is about 3 mm, the diameter of the cones at the base is about 770 μm, and the separation between the adjacent cones at the base is about 680 μm. During the fabrication process, a neodymium magnet was placed under the sample to make the embedded Co MPs arrange orderly, resulting in a subtle response to the magnetic field. Due to the effect of the applied magnetic field, Co MPs were more inclined to deposit on the tip of the cactus spine-like cone, resulting in the morphology difference on the magnetic cone surface (Figure S1, Supporting Information). The top site of the cone is much rougher than the bottom site, arising from the inhomogeneous distribution of Co MPs.

In order to investigate the magnetic response properties of the cactus-inspired cone arrays, a cylindrical NdFeB permanent magnet (≈0.7 T) fixed on a manipulator was applied on the top of the arrays, and the response of the cones was recorded by a charge-coupled device (CCD) camera (**Figure 2**). When the magnet was applied normally over the sample, the cactus spine-like cones were totally upright. Accompanying the horizontal movement of the external magnet, the cone arrays responded to the magnetic field by reversibly bending along the field. This can be attributed to the flexibility and magnetic response properties of the PDMS embedded in Co MPs. The bending intensity of the cactus spine-like cones was affected by the strength and movement speed of the applied magnetic field (Figure S3, Supporting Information). Once the magnet is removed, the cones will recover their original vertical positions. The bending actuation should be sufficiently powerful to harvest fog water or to transport macroscopic nonmagnetic objects placed over the cone arrays.

Although a series of bio-inspired fog collectors has been developed during the last years as a sustainable water source on the premise of the fog-laden flow, the design of an effective fog collector is still a challenge for its practical application, especially in the foggy regions with little wind. In this work, magnetically responsive flexible conical arrays with cactus spine-like structures were used to construct the fog collector under the quasistatic foggy atmosphere. The magnetically responsive conical array was placed at the bottom of the closed poly-methyl-methacrylate (PMMA) chamber at a temperature of 27 °C. The relative humidity inside the foggy chamber was carefully controlled at ≈80%. The cactus-inspired cone arrays vibrated regularly with a linear velocity of about 3.2 mm s^{-1} under the motion of

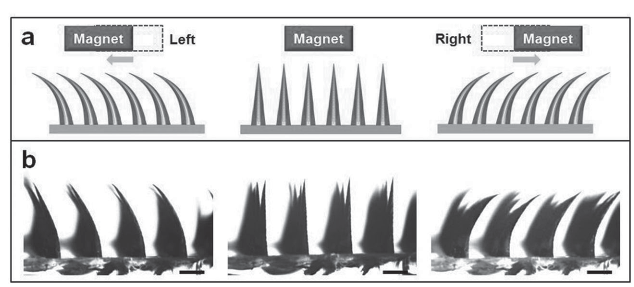

Figure 2. The magnetic responses of the cactus-inspired array under an external magnetic field. a) Schematic of the magnetically induced conical array responses to the magnetic field. When the magnet is applied directly over the sample, the cactus spine-like cones are totally upright. With the horizontal movement of the external magnet, the cone arrays respond to the magnetic field by reversibly bending along the field. b) The responses of the magnetically conical array under the magnetic field were recorded by a high-speed CCD camera. Scale bar: 1 mm.

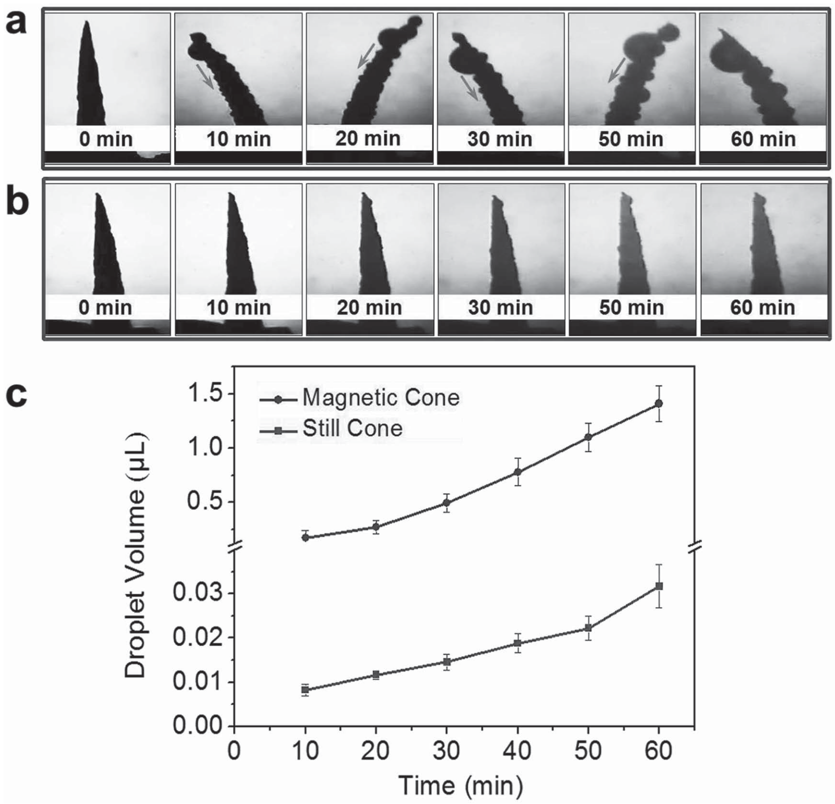

Figure 3. In situ CCD camera observation of the water collection of a magnetic cone with and without the external magnetic field in the same chamber. The deposited water drop on a) a magnetically driven cone and b) a static cone placed in the same fog chamber at different time periods. c) Relationship between the volume of the water drop on a single cone and the time of fog harvesting. Circles and squares correspond to the magnetically actuated cone and the static cone, respectively. The average efficiency of water harvesting of a magnetically driven cone is higher than that of a static one. The error bars were obtained from five repeated measurements.

the applied external magnet. Although the mist in the closed chamber is on the condition of the quasistatic state, the periodical vibration of the flexible conical arrays with cactus spine-like structures makes it possible to capture fog water.

The fog-harvesting ability of the flexible conical arrays was investigated under the external magnetic field. The size of the conical array is about 1 cm × 1 cm composed of 144 well-defined cactus-like spines. A high-speed CCD camera was used to in situ record and visualize the detailed fog collection and droplet movement processes on the cactus-inspired magnetic cones. It was found that, under the integration of the magnetic field-driven periodic vibration and the conical-structure-induced Laplace pressure difference, the cactus-like spine can effectively harvest fog water in the closed chamber filled with quasistatic mist (**Figure 3**a,c). Similar to the fog collection behavior of cactus spines found in nature, fog droplets prefer to be captured by the tip of the conical spine, resulting in the formation of a tiny water droplet on the tip. During the continuous fog-harvesting process, the fusion of the tiny droplets resulted in the release of their surface energy, which favored the motion of the water droplet.[9] The overloaded water droplet will move toward the base of the conical spine, arising from the conical-shape-induced Laplace pressure difference. After the droplet moved away from the tip, a fresh conical surface was released and a new cycle of water deposition and directional collection began. The continuous and magnetically induced fog harvesting was achieved through the successive “fusion” and “directional movement” processes (Figure S5, Supporting Information). For a single conical spine, the average fog-harvesting efficiency was about 1.41 μL h^{-1}, calculated by the modified equation of the ellipsoidal volume (Figure S6, Supporting Information).[5e] For the conical spine without the external magnetic field under the same relative humidity inside the foggy chamber, fog water was hardly captured by the spine arising from the low mist speed and the fog-harvesting efficiency was negligible (Figure 3b,c). This demonstrates that our proposed magnetically induced fog-harvesting strategy is an effective approach to collect static fog water as an alternative freshwater resource in the foggy regions. According to the World Health Organization, for a person, the minimum water requirement to sustain life is about 2.5 L per day under moderate climatic conditions.[10] In this work, the flexible conical array containing 144 spines cm^{-2} can collect about 0.2 mL h^{-1} under the quasistatic foggy environment. This indicated that basic water requirement for a person can be effectively solved by using a fog collector with 1 m^2 conical arrays to harvest fog water for only 1.25 h. Furthermore, the present magnetically induced fog collector can be fabricated in larger scale, which will improve the fog-harvesting efficiency. The present magnetically induced fog-harvesting approach may serve as a source of inspiration to optimize the existing fog collection system.

Figure 4a shows schematic representation of the mechanism for the magnetically induced fog harvesting. Generally, water harvesting was realized by the collision between the fog droplets and water collectors. Under the external magnetic field, the collision probability between fog droplets and the cone was increased and the effective fog-harvesting area was enlarged arising from the periodic vibration of the flexible conical spine. When the spine vibrates from point A to point B, it can collide with fog water in the scanning area. This is beneficial to the deposition of tiny water droplets on the spine, especially on the tip, and the improvement of fog-harvesting efficiency. According to the previous work, the conical-shape structure provided an obvious Laplace pressure difference arising from its curvature.[4f,5a] Fog water preferred to be captured by the tip site of the conical spine, which is similar to the cactus in nature. A droplet on a conical-shape surface is often driven to the side with the larger radius arising from the gradient of the Laplace pressure.[11] Therefore, the directional movement of the water droplet

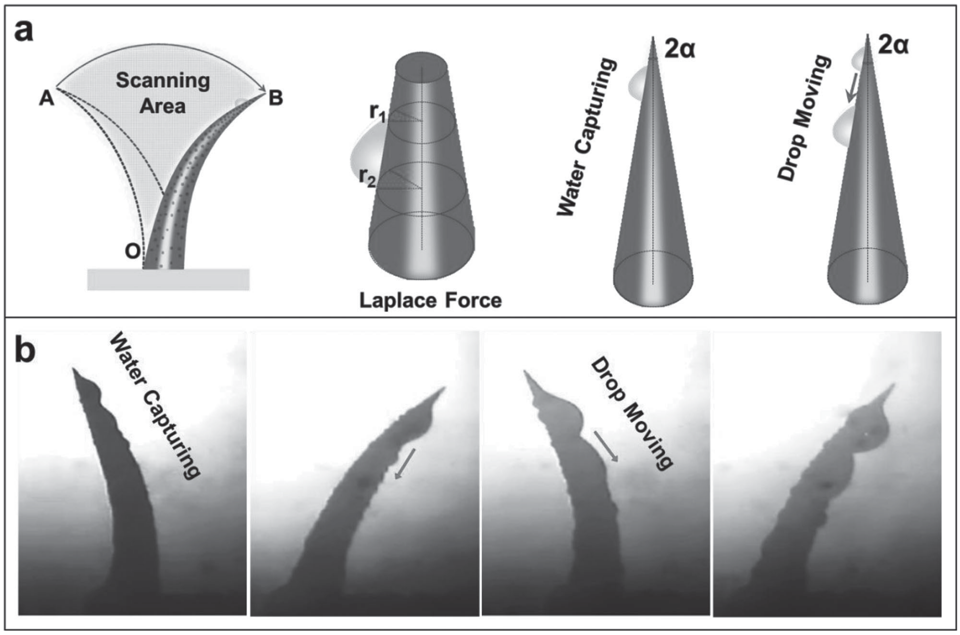

Figure 4. The water droplet was collected and transported directionally toward the base of the cone utilizing vibration and the Laplace force gradient. a) The constant vibrations of a magnetic cone significantly increases the probability of collision with fog droplets. The conically shaped surface generates a gradient of Laplace pressure from high curvature site (r_1) to low curvature site (r_2), which is the main driving force for the directional movement of droplets. b) Fog water was captured and transported toward the base of the flexible cone utilizing magnetic-induced vibrations and the Laplace pressure difference.

from the tip to the base side of the spine can be attributed to the Laplace pressure difference (ΔP) within the water droplet explained below,

$$\Delta P = -\int_{r_1}^{r_2} \frac{2\gamma}{(r+R_0)^2} \sin\alpha \, \mathrm{d}z \tag{1}$$

where r is the local radius of the magnetic cone, R_0 is the drop radius, and γ is the surface tension of water, α is the half-apex angle of the magnetic cone, and dz is the incremental radius of the cone. The gravitational force of the water droplet has little effect on the directional water collection performance.[4f,5a] As the radius of the tip (r_1) is much smaller than that of the bottom (r_2), the Laplace pressure on the spine tip is larger than that on the base. Therefore, the difference of Laplace pressure within a water droplet will serve as a driving force to push the directional movement from the tip to the base of the conical spine.

Figure 4b clearly shows that during the regular vibrations of the flexible conical spine under the external magnetic field, fog water is captured and transported toward the base of the cone driven by the Laplace pressure difference.

3. Conclusion

In conclusion, magnetically induced fog harvesting under windless conditions was achieved through the integration of cactus-inspired spine structures and magnetically responsive flexible conical arrays. Static fog water can be spontaneously and continuously captured and directionally transported from the tip to the base of the spine through periodic vibration of the flexible conical spine driven by the external magnetic field and the Laplace pressure difference arising from the conical shape of the spine. Furthermore, the present magnetically induced fog collector can be fabricated in larger scale and can therefore meet the demand for the basic water requirement of a person in a short period of time. The magnetically induced fog-harvesting system should have promising applications in windless and foggy regions, and could serve as a source of inspiration to further optimizations of oil mist purification and fog-water-harvesting strategies.

4. Experimental Section

Fabrication of Magnetically Conical Array: A series of organized conical holes were constructed on the polyvinyl chloride (PVC) polymer sheet through a mechanically punched approach. To obtain a regular magnetically conical array, a commercial sewing needle was attached to a jet dispensing system to prick conical holes in a piece of PVC (with a thickness of 5 mm) first. Then, 200 mg Co MPs in microscale (purchased from Sigma-Aldrich; average diameter of 2 μm) was dispersed uniformly into each hole of the array. The PDMS prepolymer (contained 0.1 equivalent curing agents; purchased from Dow Corning, SYLGARD 184) was cast on the template filled with Co MPs with assistance of vacuum pumping. For making the Co MPs in vertical arrangement in the holes, the sample was placed on the top of a permanent magnet (60 mm in diameter, 50 mm in thickness) with a superficial magnetic field intensity of about 0.9 T in the process of degassing and curing. After curing, the PVC template was dissolved in a prepared tetrahydrofuran (THF) solution for 24 h. The dissolving process was carried out at room temperature to minimize the probable swelling of PDMS matrix. After dissolving, the magnetically conical array with the size of about 3 mm height, 770 μm diameter at the base, and 680 μm separation between the adjacent cones was obtained.

Experiments on the Water-Collecting Ability of Magnetically Conical Array: The magnetically conical array was carefully fixed upward in the closed PMMA chamber with a size of 30 cm (length) × 30 cm (width) × 30 cm (height). The static foggy atmosphere was provided previously by an ultrasonic humidifier (YC-E350, Beijing YADU Science and Technology Co., Ltd) and the relative humidity inside the foggy chamber was carefully controlled at about 80%. The whole process was recorded by the optical microscope and CCD components of the OCA40 system (Data-Physics, Germany) at room temperature.

Characterization of Magnetically Conical Array: SEM images of the samples were obtained with a field-emission SEM(JSM-6700F, Japan). The optical images of the magnetically conical array were recorded by a digital camera (Canon Powershot A1100IS).

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements

The authors appreciate the financial support of the National Natural Science Foundation of China (21273016), National Basic Research Program of China (2013CB933003), Program for New Century Excellent Talents in University, Beijing Higher Education Young Elite Teacher Project, Key Research Program of the Chinese Academy of Sciences (KJZD-EW-M01), 111 Project (grant number B14009), and the Fundamental Research Funds for the Central Universities.

Received: July 6, 2015
Published online: August 21, 2015

[1] a) J. Yeston, R. Coontz, J. Smith, C. Ash, *Science* **2006**, *313*, 1067; b) T. Oki, S. Kanae, *Science* **2006**, *313*, 1068; c) I. A. Shiklomanov, J. C. Rodda, *World Water Resources at the Beginning of the Twenty-first Century*, Cambridge University Press, Cambridge **2004**.
[2] *Global Risks 2015*, 10th ed., World Economic Forum, Geneva **2015**.
[3] P. Gandhidasan, H. I. Abualhamayel, *Water Environ. J.* **2007**, *21*, 19.
[4] a) A. R. Parker, C. R. Lawrence, *Nature* **2001**, *414*, 33; b) W. J. Hamilton, M. K. Seely, *Nature* **1976**, *262*, 284; c) Y. Zheng, H. Bai, Z. Huang, X. Tian, F. Q. Nie, Y. Zhao, J. Zhai, L. Jiang, *Nature* **2010**, *463*, 640; d) M. Ebner, T. Miranda, A. Roth-Nebelsick, *J. Arid Environ.* **2011**, *75*, 524; e) H. G. Andrews, E. A. Eccles, W. C. E. Schofield, J. P. S. Badyal, *Langmuir* **2011**, *27*, 3798; f) J. Ju, H. Bai, Y. M. Zheng, T. Y. Zhao, R. C. Fang, L. Jiang, *Nat. Commun.* **2012**, *3*, 1247; g) A. Roth-Nebelsick, M. Ebner, T. Miranda, V. Gottschalk, D. Voigt, S. Gorb, T. Stegmaier, J. Sarsour, M. Linke, W. Konrad, *J. R. Soc. Interface* **2012**, *9*, 1965; h) K. Liu, X. Yao, L. Jiang, *Chem. Soc. Rev.* **2010**, *39*, 3240.
[5] a) M. Y. Cao, J. Ju, K. Li, S. X. Dou, K. S. Liu, L. Jiang, *Adv. Funct. Mater.* **2014**, *24*, 3235; b) M. Fessehaye, S. A. Abdul-Wahab, M. J. Savage, T. Kohler, T. Gherezghiher, H. Hurni, *Renewable Sustainable Energy Rev.* **2014**, *29*, 52; c) Y. Chen, Y. M. Zheng, *Nanoscale* **2014**, *6*, 7703; d) K. C. Park, S. S. Chhatre, S. Srinivasan, R. E. Cohen, G. H. McKinley, *Langmuir* **2013**, *29*, 13269; e) J. Ju, X. Yao, S. Yang, L. Wang, R. Z. Sun, Y. X. He, L. Jiang, *Adv. Funct. Mater.* **2014**, *24*, 6933; f) J. Ju, Y. M. Zheng, L. Jiang, *Acc. Chem. Res.* **2014**, *47*, 2342; g) R. P. Garrod, L. G. Harris, W. C. E. Schofield, J. McGettrick, L. J. Ward, D. O. H. Teare, J. P. S. Badyal, *Langmuir* **2007**, *23*, 689; h) H. Bai, R. Sun, J. Ju, X. Yao, Y. M. Zheng, L. Jiang, *Small* **2011**, *7*, 3429; i) J. Ju, K. Xiao, X. Yao, H. Bai, L. Jiang, *Adv. Mater.* **2013**, *25*, 5937; j) M. Y. Cao, J. S. Xiao, C. M. Yu, K. Li, L. Jiang, *Small* **2015**, DOI: 10.1002/smll.201500647.
[6] R. S. Schemenauer, P. Cereceda, *Ambio* **1991**, *20*, 303.
[7] J. N. Myers, *Sci. Am.* **1968**, *219*, 74.
[8] a) K. Li, J. Ju, Z. Xue, J. Ma, L. Feng, S. Gao, L. Jiang, *Nat. Commun.* **2013**, *4*, 2276; b) P. Bian, T. J. McCarthy, *Langmuir* **2010**, *26*, 6145.
[9] a) J. B. Boreyko, C. H. Chen, *Phys. Rev. Lett.* **2009**, *103*, 184501; b) X. Jin, X. Zhang, Y. Peng, M. Cao, H. Liu, X. Pei, K. Liu, L. Jiang, *Adv. Eng. Mater.* **2015**, *17*, 961.
[10] P. H. Gleick, *Water Int.* **1996**, *21*, 10.
[11] É. Lorenceau, D. Quéré, *J. Fluid Mech.* **2004**, *510*, 29.