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Review of directional liquid transport on surfaces with different structures

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Abstract. Directional liquid transport has many cutting-edge applications, such as fog collection, agricultural drip irrigation, biochemical microreactors, water harvesting, non-powered micro-drug delivery, thin-film lubrication etc. There are many surfaces or linear structures in the natural systems can occur directional transport of water. In this paper, two bionic structures inspired by natural structures and two artificially fabricated surface structures are presented and their flow laws and mechanical mechanisms are described. Thereby, it is analysed that surface-driven external forces, such as the gradient of surface energy and the gradient of Laplace pressure, and surface pinning in other directions are the key points to drive the directional flow of liquids.

Keywords: directional liquid transport, Young’s equation, surface energy, Laplace pressure.

1. Introduction

Directional water transport is not only widespread in nature, such as the unidirectional transport of water from the inside to the outside on peristome of the Nepenthes alata and directional water transport that takes place on three-dimensional capillary ratchet of the Araucaria leaves, but also has its practical applications even in life, such as agricultural drip irrigation, desalination of seawater, non-powered microdrug delivery, etc. Currently, scientists drive the directional flow of liquids on solid surfaces mainly by designing and fabricating surface structures. Specifically, these include, the bionic structures based on natural structures, and artificial structures. This paper first introduces the structures of natural structured surfaces, such as the surfaces of Nepenthes’ peristome and Araucaria leaf, describes how liquids transport on these structured surfaces, and then introduces the principles of flow, i.e., why these natural surfaces can drive the directional flow of liquids. Then, this paper introduces the structures, flow laws and flow mechanisms on the bionic surfaces and on the artificial surfaces. Based on this, this paper summarizes the key conditions that need to be satisfied for surface structures to drive the directional transport of liquids, and these laws provide strong theoretical support for future surface design engineering.

2. Directional liquid transport on a variety of surfaces

2.1. Directional liquid transport on the surfaces of natural materials

It is widely existed in natural world that liquid transport directionally and continuously on the surface of many living things include animals and plants, such as araucaria leaf's surface, the Nepenthes alata's peristome surface, etc [1-5].

2.1.1. The Nepenthes alata's peristome surface: Directional liquid transport. Six years ago, Chen et al. report the continuous directional liquid transport that occurred on Nepenthes alata's peristome surface [2,5].

Structures of the Nepenthes alata's peristome surface is revealed using scanning electron microscopy. The results show that the surface is consisted of regular radial first-order microgrooves [2-4]. Every microgroove that is first-order contains about ten microgrooves that are second-order. Arch-shaped microcavities distributed regularly in each microgroove considered second-order. Microcavity has an enclosed top that is decorated with an acute edge. The fluid dynamics of liquid on the Nepenthes alata's peristome surface is observed utilizing the high-speed camera. When a drop of water is deposited on the surface, the water transport directionally towards the direction of the outer edge, however, it cannot transport towards the direction of the inter edge. Moreover, the water transport is confined within the first-order microgroove, therefore, it cannot spread laterally out of the initial deposition region.

Why the water droplet transport directionally and continuously on the surface of Nepenthes' peristome. Firstly, the transport of water from the inside to the outside of the peristome occurs through the continuous filling of individual microcavities, where the capillary rise of water can happen over a wedge corner of the microcavity formed by two vertically intersecting hydrophilic surfaces, filling water into microcavity through the air being pushed out, and eventually concentrates at the microcavity's front section. A filling of a microcavity is started before the filling of the previous microcavity is completed, attributed to the fact that the adjacent microcavities are overlapping. Secondly, edge angle is an angle formed by the two surfaces of a sharp edge. When the size of the edge angle is 2~8°, it is conducive to water being pinned to microcavity's acute edges and prevents the peristome from being wetted from the outside to the inside. In conclusion, the symmetrical and top-closed taps in the peristome causes a stronger capillary rise of the water than a normal one. The sharp edges of the microcavities are capable of pinning reverse water. Next to the surface of the peristome, the combination of the two allows the water to be transported in a rapid and uninterrupted directional manner.

2.1.2. The Araucaria leaf's surface: Directional liquid transport. In 2021, Feng et al. were inspired by the Araucaria leaf, and thus produced three-dimensional capillaries in which the ratchet can cause directional steering of the liquid [1,6-8].

The Araucaria leaf has three-dimensional (3D) periodically arranged ratchets which are composed of transverse and longitudinal reentrant curvatures. The Araucaria leaf–inspired surface (ALIS), that made by Chu et al. using 3D printing technology, consists of many parallel rows of ratchet arrays that the liquids are sucked in and out by capillary action [1].

When studying the transport of water-ethanol mixtures with different mass fractions of ethanol (c) which have different surface tensions on the Araucaria leaf. The surface tension decreased from 72 mN/m to 29 mN/m with the change of c from 0% to 40%. On a surface which has the same material as ALIS, the liquid contact angle increases as the tension of surface, γ, increases. When $c \leq 10\%$, liquid will only propagate against the direction of ratchet-tilting. When c measures between 40% and 10%, bidirectional transport of liquid will occur. When c is equal to or greater than 40%, liquid will strictly propagate with ratchet-tilting's direction. When θ, the angle of contact at its equilibrium, rises into ~82° from ~20°, direction of transport will change into being backward from being forward, and crossover will happen when θ measures $42° \pm 5°$, showing a mode of transport that is bidirectional.

As seen from the experimental results. First, the liquid with low surface tension tending to the ratchet-tilting direction and the liquid with high surface tension choosing the reverse direction [1]. Second, the ability of the fluid to turn in different directions and to transport quickly under control at different surface tensions is due to the asymmetric contact lines pinned by the transverse and longitudinal reentrant curvature. In addition, when a slopy angle φ, where φ is equal to or smaller than 90° but greater than 0°, is paired with the Araucaria leaf, transport that is directional can still be maintained, even though the transmission distances decrease with the increase of φ.

2.2. Artificial structures' surfaces: Directional liquid transport

2.2.1. Asymmetric structures' surface: Directional liquid transport. In 2010, Chu et al. found that unidirectional transport of liquids can also occur on the surface of specific asymmetric nanostructures [9].

Arrays of asymmetric nanopillars with a 3.5 μm spacing, heights between 10 μm and 6 μm, as well as diameters between 750 nm and 300 nm were fabricated. Using a Cartesian coordinate system, the pillars are deflected in the +X direction. The chemical vapor deposition method can coat the surface of the nanopillar with different polymers that change the surface energy of the deionized water, resulting in a change in the angle of contact that is intrinsic.

Unidirectional transport of DPBS and water that is deionized can occur on the surface of an asymmetric nanostructure with a nanopillar angle of deflection that measures 8.7°along with a 62° angle of contact that is intrinsic, and the same phenomenon as above was produced on the surface of another polymer coating with a nanopillar deflection angle of 12° along with an 80° angle of contact that is intrinsic. The liquids all propagate mainly towards the direction of +X, and the line contact pinning directions of -X and Y axis. Film that is liquid will transport strictly when line of contact can meet the following column rows. At which point, the critical angle θcr must equal to or surpass the liquid's local equilibrium angle of contact, θeq, based on the equation of Young. When θeq measures smaller than θcr, among the nanopillars will film that is liquid propagate. When θeq measures greater than θcr, film that is liquid will be pinned.

Therefore, propagation of film that is liquid can be defined as that the liquid contact angle cannot be smaller than the lowest energy state θeq of Young's equation. Furthermore, liquid's angle of contact that is intrinsic on the surface of polymer as well as prepared nanopillars' asymmetric structure will determine unidirectional spreading of the liquid and pinning other directions.

2.2.2. Dual scale arrays' surface: Directional liquid transport. In 2018, Wang et al. produced dual-scale array samples capable of enabling the unidirectional transport of water using 3D (three-dimensional) printing equipped with DLP (digital light processing) [10].

The dual-scale sample is an array of macroscale islands that is in the shape of an "A" and embedded on the surface of island are microgrooves that appear parallel. Individual islands are taper in width and have the outline and sharp edge of italicized letter 'A'. From the lateral view, they radiate obliquely on the substrate at a thickness that is consistent through the bottom to the top, which have good mechanical strength. The edges of the A-shaped islands are stepped.

In general, unidirectional transport cannot be realized when the inclination angle α= 0°. Under the condition where α does not equal to 0°, one can comprehend the transport that is unidirectional if the value of θ fits into a specific scope. If θ is overly insufficient, the liquid will unfold in the directions of both +X and −X. If θ is a large value, it will lead to reverse unidirectional transport. If the value of α falls between 75. 0° and 45. 0°, the substance will unfold towards the direction of +X. When a specific period of time has passed, the substance will start to unfold towards the direction of −X as well. When the value of α is either 15.0° or 30.0°, the substance will simultaneously unfold toward both the directions of −X and +X. However, the distance of unfolding in the direction of −X is shorter compared to that of the other direction. When α = 0° (island is perpendicular), the substance will unfold toward both directions in a symmetrical manner, which makes transport that is unidirectional impossible.

What causes the fluid to be continuously and directionally transported throughout the array. First, when the oil is to spread all over the place and reach junction of the root and substrate of the island, it is rapidly held in place and rises capillary along the nether slope, causing a concave half-moon shaped liquid surface to appear at the junction, and in the direction of +X, its presence causes the liquid to receive some extra Laplace pressure determined by half-moon shaped as well as the liquid's surface tension [10]. As oil continues to be deposited, the additional Laplace pressure causes it to transport in the +X direction so that the following island can be reached. Second, this capillary-driven directional process of transport of oil that happens within microgrooves located at the next island's root is caused by a large additional Laplace pressure due to the very small radius of the liquid level concavity in the microgrooves [11]. The above two points cause the liquid to be continuously transported in a directional manner across the surface of the dual-scale array.

3. Conclusion

In this paper, we introduce and summarize the directional liquid transport technologies, including surface structures of natural organisms (e.g., the peristome of Nepenthes alata capable of unidirectional liquid transport from the inside to the outside), bio-inspired structures (e.g., the Araucaria leaf-inspired surface (ALIS) that mimics the morphological features of Araucaria leaf on which unidirectional transport of liquid can occur) and artificial structures (directed liquid transport occurring on asymmetric nanostructured surfaces and dual-scale array surfaces). For each method, we present the characteristics of the surface structure, the flow dynamics of the liquid, and the mechanisms that drive and direct the flow. The unique microcavity structure of Nepenthes alata can make water continuously fill in, and the edge angle can pin the water transport in the opposite direction of the spreading, thus making the water continuous and rapid directional transport. The Araucaria leaf take advantage of the principle that liquids tend to move in the direction of reduced surface tension, and the asymmetric contact lines pinned by the transversal and longitudinal reentrant curvatures enable the liquid to turn and move in different directions with different surface tensions. The artificially fabricated geometrically asymmetric nanostructures enable continuous directional transport of liquids by varying the nanopillar geometry of their surfaces, and the liquids' angles of contact that are intrinsic at different surface coatings of polymer. Dual-scale array surfaces enable continuous directional transport of liquids in the target direction by creating a Laplace pressure difference. In addition, we summarize two key points from the four examples above that determine whether a liquid can flow in a directional manner, as follows. First, spreading of the liquid in any direction other than the direction of motion will be pinned. Then, an external driving force is needed to drive the flow of the liquid, such as those generated by different surface energy gradients and Laplace pressure gradients, as well as the tendency of the liquid itself to flow from a high surface energy region to a low surface energy region [10,11]. These two cues enhance the understanding of the surface motion of liquids and help in the design and fabrication of artificial structures that more precisely direct the directional flow of various liquids.

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