

(43) International Publication Date
28 September 2017 (28.09.2017)

(51) International Patent Classification:

F28F 17/00 (2006.01) F28B 1/00 (2006.01)
F24F 13/00 (2006.01)

(21) International Application Number:

PCT/IB2017/000370

(22) International Filing Date:

23 March 2017 (23.03.2017)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

62/390,272 24 March 2016 (24.03.2016) US

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(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— with international search report (Art. 21(3))

[Continued on next page]

(54) Title: ENHANCED CONDENSED WATER CAPTURE BY ALTERNATE ARRANGEMENT OF HETEROGENEOUS WETTING SURFACES

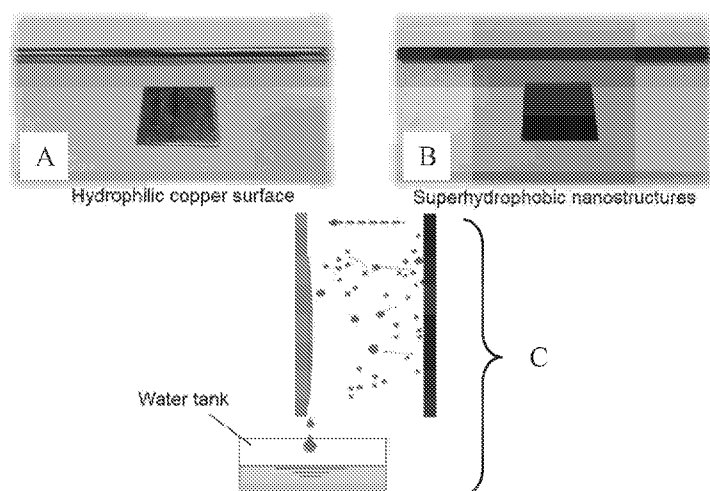


FIG. 1

(57) Abstract: Systems and methods for capturing condensed liquid, such as water, in heat transfer devices are provided. Heterogeneous wettable surfaces are also provided. A system can include a first structure having at least one surface substantially wettable by the liquid to be captured and a second structure having at least one surface substantially non-wettable by the liquid to be captured.



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- *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))*

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DESCRIPTION

ENHANCED CONDENSED WATER CAPTURE BY ALTERNATE ARRANGEMENT
OF HETEROGENEOUS WETTING SURFACES

10

CROSS REFERENCE TO RELATED APPLICATION

This application claims the benefit of U.S. Provisional Patent Application Serial No. 62/390,272, filed March 24, 2016, the disclosure of which is hereby incorporated by reference in its entirety, including any figures, tables, or drawings.

15

BACKGROUND

Efficient water capture technology is desirable for energy saving in various heat transfer devices. Recent studies have shown that the thermal-hydraulic performance of a heat transfer device is significantly influenced by its surface characteristics. Conventional heat exchangers designed to conduct heat transfer are made of metallic materials that are hydrophilic in terms of wetting. During a process such as, for example, dehumidifying or cooling, these wettable metallic heat transferring surfaces allow atmospheric moisture to condense upon contact with, and form a liquid film over, the entire surfaces. The condensate accumulates to form a film on the hydrophilic surface and is difficult to be removed, resulting in large thermal resistance between the air and condensing surface, which can significantly degrade the performance of the heat exchangers in continuous operation.

To address this challenge, a general approach in the related art has been to make the heat transferring surface non-wettable by water in order to achieve dropwise, instead of film-like, condensation. By modifying the heat exchanger surface with a hydrophobic material, the condensate forms droplets, which can easily roll off the surface when a critical droplet size is reached.

Other related arts have reported on designing a heat exchanging surface capable of accommodating a combination of wetting behaviors in the hope of improving the rate of condensation and the overall efficiency of water capture. Chaudhury *et al.*, for example, have developed a central-hydrophobic surface with radially outward gradient of chemical composition prepared by diffusion-controlled silanization¹. Guided by the surface energy gradient thus created and propelled by energy released during coalescence, small droplets can spontaneously depart from the surface with a speed that is two orders of magnitude higher than those observed under ambient conditions. As compared to the film-wise condensation

5 mode, the heat transfer coefficient of heat exchangers can be increased by at least a factor of 3.

Devices described by this and other similar related arts (see, for example, References 2-4) still face a number of drawbacks. First, the processes for fabricating hybrid hydrophilic-hydrophobic surfaces are complicated due to the need for creating heterogeneous chemical
10 compositions on a single surface. Second, the design parameters for a hybrid surface pattern such as, for example, profile, length scale, and wettability gradient are still unclear for industrial applications. Third, the distribution characteristics of condensed droplets including density, departure size, and surface coverage achieved at the dropwise state still cannot satisfy the demanding requirement for energy saving. For example, during dropwise
15 condensation, most of the heat transfer is conducted through small droplets with diameters of less than 10 μm , yet a conventional hydrophobic surface is usually covered by droplets larger than 100 μm because they only roll off the surface when they reach the capillary length, which is approximately 2 mm for water.

These and other challenges are yet to be addressed for achieving increased heat
20 transfer efficiency and lowered manufacturing cost in heat transferring systems.

BRIEF SUMMARY

Embodiments of the subject invention provide systems and methods of making and using the same for capturing condensed liquid, particularly water, in heat transfer devices.

25 In an embodiment, a condensate capturing system can comprise a first structure having at least one hydrophilic (or substantially hydrophilic) surface and a second structure having at least one superhydrophobic (or substantially superhydrophobic or biphilic) surface with jumping droplet property in condensation, wherein the two structures are positioned such that the (substantially) hydrophilic surface is opposite to and separated from the
30 (substantially) superhydrophobic surface. The first and second structures can be positioned parallel to, or at an angle with, each other. The two structures can have the same or different geometries.

In some embodiments, the (substantially) hydrophobic surface comprises functionalized nanoscopic three-dimensional structures on top of the surface. In some
35 embodiments, the (substantially) hydrophobic surface is a heterogeneous wetting surface that comprises a plurality of hydrophilic (or substantially hydrophilic) regions exposed through functionalized hydrophobic nanoscopic three-dimensional structures.

5 Embodiments of the subject invention further provide heterogeneous wetting surfaces (e.g., a biphilic surface) and methods of making the same.

 Advantageously, systems and methods provided herein can not only enable efficient capture of condensed liquid (e.g., water) from atmosphere but also afford a variety of design possibilities to accommodate different efficient heat transfer applications.

10 BRIEF DESCRIPTION OF DRAWINGS

Figure 1A illustrates a hydrophilic copper surface according to an embodiment of the subject invention.

Figure 1B illustrates a superhydrophobic surface comprising a plurality of
15 nanostructured structures protruding from the surface according to an embodiment of the subject invention.

Figure 1C is a schematic showing a water capture method using hydrophilic and superhydrophobic surfaces in parallel, according to an embodiment of the subject invention. The arrows indicate the trajectory of jumping droplets from the superhydrophobic surface to
20 the hydrophilic surface.

Figure 2A is a scanning electron microscope (SEM) image showing a nanostructured surface comprising CuO formed via anodization.

Figure 2B is an SEM image showing a nanostructured surface comprising Al₂O₃ formed via anodization.

25 **Figure 2C** shows multiple condensed droplets on a superhydrophobic surface simultaneously departing from the surface upon coalescence.

Figure 2D shows self-jumping droplets accumulate on a hydrophilic surface set 3 mm away opposite to a superhydrophobic surface. The image was captured via a high-speed camera in a magnified view.

30 **Figure 3A** is a schematic showing a heat exchanger utilizing an alternating hydrophilic surface-superhydrophobic surfaces design according to an embodiment of the subject invention. The arrows indicate the trajectory of the jumping droplets.

Figure 3B is a schematic showing a heat exchanger utilizing an alternating hydrophilic-superhydrophobic surfaces design according to an embodiment of the subject
35 invention. The arrows indicate the trajectory of the jumping droplets.

Figure 4A is a front-view schematic showing a dew-harvesting collector utilizing an alternating hydrophilic-superhydrophobic surfaces design according to an embodiment of the subject invention. The arrows indicate the trajectory of the jumping droplets.

5 **Figure 4B** is a side-view schematic showing a dew-harvesting collector utilizing an alternate hydrophilic-superhydrophobic surfaces design according to an embodiment of the subject invention. The arrows indicate the trajectory of the jumping droplets.

Figure 5 is a schematic showing a distillation tube bundle utilizing an alternate hydrophilic-superhydrophobic surfaces design according to an embodiment of the subject
10 invention. The light and dark lines represent the hydrophilic and superhydrophobic surfaces, respectively. The arrows indicate the trajectory of the jumping droplets.

Figure 6A is a schematic showing a heterogeneous wetting surface comprising an exposed hydrophilic condensing area on the bottom denoted as the “metal substrate” and superhydrophobic nanostructures deposited atop the hydrophilic surface, according to an
15 embodiment of the subject invention. The condensed droplets assume a partial-Wenzel morphology.

Figure 6B is an SEM image showing a stochastic nylon mask pre-sprayed on a copper (*i.e.*, hydrophilic) substrate according to an embodiment of the subject invention.

Figure 6C is an SEM image showing a nanostructured CuO (*i.e.*, superhydrophobic)
20 surface with exposed hydrophilic substrate after surface anodization and mask lift-off, according to an embodiment of the subject invention.

Figure 7A is an SEM image showing a nylon mask post-spray atop a nanostructured CuO surface according to an embodiment of the subject invention.

Figure 7B is an SEM image showing a nylon mask post-spray atop a nanostructured
25 Al₂O₃ surface according to an embodiment of the subject invention.

Figure 7C shows images, at different time points, of the condensation dynamics on an Al-based heterogeneous wetting surface according to an embodiment of the subject invention. Due to the hydrophilic micropatches on top of the condensing interface, the heterogeneous wetting surface of embodiments of the subject invention can achieve higher
30 droplet density as well as an efficient droplet departure rate.

Figure 7D shows images, at different time points, of the condensation dynamics on an Al-based superhydrophobic surface according to an embodiment of the subject invention.

DETAILED DESCRIPTION

35 Embodiments of the subject invention provide systems and methods of making and using the same for capturing condensed liquid, particularly water, in heat transfer devices. Advantageously, embodiments provided herein can be used in heat exchange components for condensation heat transfer and/or water collection with improved efficiency and reduced

5 manufacturing cost. Particularly exemplary applications of embodiments of the subject invention include, but are not limited to, heating ventilation air conditioning (HVAC) systems, dehumidifiers, water harvesting systems, heat pumps, and desalination systems.

Water condenses on cool surfaces when its temperature is reduced to below the saturation vapor temperature (*i.e.*, the dew point temperature). The latent energy of water
10 vapor is released during phase transition (*e.g.*, condensation), and heat is transferred to the condensing surface. Depending on the wettability of the condensing surface, the condensed liquid may be in the form of a film or discrete droplets, termed as filmwise or dropwise condensation, respectively. To maintain a desired high condensation and hence, heat transfer, rates, dropwise condensation is preferred to filmwise condensation because the gravity-driven
15 sweeping of water droplets can significantly decrease the thermal resistance of the condensate on the surface. For example, the rates of dropwise condensation can be as much as an order of magnitude larger than those associated with filmwise condensation.

However, the droplet nucleation rate on the hydrophobic surface is significantly lower than that on the hydrophilic surface because of the higher water nucleation energy barrier of
20 hydrophobic surfaces. Thus, an efficient condensation surface that enables increased droplet nucleation density, reduced droplet departure size, and minimal thermal barrier demands a synergistic cooperation of these advantages inherent in both modes of dropwise and filmwise condensation simultaneously.

In light of the need presented above, embodiments of the subject invention provide
25 condensate capturing systems to address the need presented above. In an embodiment, a condensate capturing system can comprise a first structure having at least one hydrophilic (or substantially hydrophilic) surface and a second structure having at least one hydrophobic (or substantially hydrophobic) surface, wherein the two structures are positioned such that the (substantially) hydrophilic surface is opposite to and separated from the (substantially)
30 hydrophobic surface. A direct-current electric field can be applied across the (substantially) hydrophilic surface and the (substantially) hydrophobic surface to enhance water droplet movement from the hydrophobic surface to the hydrophilic surface.

The separation distance between the first structure and the second structure can be between, for example, about 1 mm and about 15 mm, preferably between about 2 mm and
35 about 6 mm, and most preferably between about 3 mm and about 5 mm (all ranges inclusive of the endpoints). Importantly, the separation distance can be determined based upon the devices in which the capturing system is applied, provided that the spontaneous departure of the condensate droplets can be accommodated across the separation distance.

5 In some embodiments, the first structure comprises at least one surface that is substantially wettable (*e.g.*, hydrophilic) by the condensing liquid, which is water in most heat transfer applications. Most metallic materials involved in heat exchanging devices (*i.e.*, metals with advantageous thermal conductivity) are hydrophilic without further surface modification. Non-limiting examples of a hydrophilic metallic surface include copper,
10 aluminum, zinc, iron, associated metal oxides thereof, and a combination of all of the above.

In some embodiments, the second structure provides at least one surface that is non-wettable (or substantially non-wettable) (*e.g.*, hydrophobic or superhydrophobic) by the condensing liquid. In the case that the condensing liquid is water, the hydrophobicity of the surface can be achieved by chemically modifying the surface with a plurality of three-
15 dimensional nanoscopic structures on top of the substrate, followed by functionalization of the structures with one or more hydrophobic compounds such as self-assembled monolayers (SAMs), including a number of thiol (*e.g.*, sulfur-based ligands) and silane (*e.g.*, silicon-based ligands) species with either hydrogenated and/or fluorinated end groups. Other surface functionalization materials include ultra-thin fluoropolymer coatings (*e.g.*,
20 polytetrafluoroethylene and parylene), noble metals, and rare earth oxides. The nanoscopic structures can be, for example, between about 1 nm and about 500 nm in apex diameter, between about 0.5 μm and about 20 μm in height, and between about 0.1 μm and about 5 μm in pitch. In some embodiments, the resulting three-dimensional structures are needle-like and closely packed to cover (or substantially cover) the underlying metal substrate (see, for
25 example, SEM images of CuO structures in Figure 2A and of Al_2O_3 structures in Figure 2B).

In an embodiment, the plurality of three-dimensional structures can be formed on a metallic surface when the surface is subjected to anodization in the presence of an alkaline solution selected from sodium hydroxide, potassium hydroxide, and a combination thereof. In some embodiments, the nanostructures can be formed by chemical etching or a number of
30 other synthesis procedures in accordance with the materials involved and the applications desired.

“Superhydrophobic” as used herein, refers to a surface on which the apparent contact angle of a droplet of water exceeds 150° and the contact angle hysteresis is smaller than 5° , allowing the droplet to depart from the surface spontaneously by coalescence at micrometric
35 length scales on the order between about 10 μm and about 100 μm (Figure 2C). Smaller droplets formed on a superhydrophobic condensing surface (as compared with droplets formed on a conventional hydrophobic surface) reduce thermal resistance of the condensate during continuous condensation. In some embodiments, condensed droplets capable of

- 5 jumping off a superhydrophobic surface can result in a heat transfer rate approximately 30% higher than those condensed on a conventional hydrophobic surface.

It is important to note that despite improved heat transfer rate, jumping droplets can easily vaporize again due to the large surface-to-volume ratio afforded by the three-dimensional structures on superhydrophobic surfaces. Advantageously, a hydrophilic surface
10 positioned in close proximity to the superhydrophobic surface allows the microscale jumping droplets to accumulate and coalesce for more efficient water collection (Figure 2D). In some embodiments, the hydrophilic surface is positioned parallel to the superhydrophobic surface (*e.g.*, Figure 3A). In some embodiments, the hydrophilic surface can be positioned at an angle with the superhydrophobic surface. Many embodiments provide that the two surfaces can be
15 positioned perpendicular to (*e.g.*, Figure 4A) or at an acute angle (*e.g.*, Figure 4B) with each other.

Figure 1C illustrates the mechanism of condensation and removal of water by an exemplary embodiment of the subject invention wherein a hydrophilic surface (Figure 1A) is positioned parallel to a superhydrophobic surface (Figure 1B). In an embodiment, a film of
20 condensate formed on the hydrophilic surface can absorb the jumping droplets ejected from the superhydrophobic surface and effectively prevent the rapid vaporization.

In some embodiments, the hydrophilic surface and the superhydrophobic surface belongs to a first and a second structure, respectively (see, for example, Figures 3A, 4A, 4B, and 5). In some embodiments, the first and the second structure can have the same geometry.
25 In alternative embodiments, the first and the second structure can have different geometry. In some embodiments, the two surfaces are the opposite sides of the same structure (see, for example, Figure 3B).

In some embodiments, the non-wettability of the condensing surface of the second structure can be achieved by modifying the metallic substrate to have a hybrid of hydrophilic
30 and hydrophobic (*e.g.*, superhydrophobic) structures on the same surface, hereafter denoted a “heterogeneous wetting surface.”

Many embodiments provide that the first and the second structures, while separated from each other, can be positioned parallel to or at an angle with each other. Further embodiments provide that the two structures can have the same or different geometries.

35 In an embodiment, a dehumidifier employing alternate arrangement of a hydrophilic surface opposite a superhydrophobic surface as provided herein demonstrates that, under standard testing conditions (*i.e.*, a dry bulb temperature of approximately 26.7 °C and a

- 5 relative humidity of approximately 60%), a water collection efficiency that is approximately 2.5 times higher than untreated surfaces, as shown in Table 1 below.

Table 1. Comparison of water collection on hydrophilic and hybrid surfaces

Case	Surface area (cm ²)	Time (h)	Water collection (ml)	Rate (ml·h ⁻¹ ·m ⁻²)
Hydrophilic (HL)	104.8	1	1.467	139.98
		6	8.983	142.85
Heterogeneous (HET) HL	HET: 36	1	3.492	HET: 696.98
	HL: 68.8	6	20.895	HET: 694.34

- 10 As demonstrated herein, homogeneous wettability (*i.e.*, comprising surface structures that predominately afford either hydrophilicity or hydrophobicity, but not both) of a condensing surface results in either poor water capture, as in the case of a hydrophobic surface, or substantial liquid adhesion, as in the case of a hydrophilic surface. The combination of hydrophilic and superhydrophobic properties is imperative for further
15 development of advanced condensing interface. Although related arts have reported on fabricating heterogeneous wetting features by methods such as photolithography and laser processing, these techniques are complicated and expensive for large-scale industrial manufacturing.

- Embodiments of the subject invention further provide heterogeneous wetting surfaces
20 and methods of making the same. In an embodiment, a heterogeneous wetting surface comprises a plurality of hydrophilic regions exposed through functionalized hydrophobic three-dimensional nanoscopic structures (Figure 6A).

- Instead of using conventional photolithography or direct laser manufacturing, fabrication methods provided herein can employ electrospray to first form a mask of
25 randomly distributed features (*i.e.*, a stochastic mask) on the hydrophilic substrate, followed by subsequent surface modification (*e.g.*, chemical etching, surface anodization, *etc.*). Advantageously, methods provided herein reduce cost and complexity associated with manufacturing three-dimensional nanostructures.

- In some embodiments, by changing the order and/or parameters of the electrospray
30 and the subsequent surface chemical treatments (*e.g.*, surface oxidation and

functionalization), the topography of the heterogeneous wetting surface can be modified to accommodate different heat transfer applications and condensation environments. In an embodiment, the mask can be applied prior to the chemical treatments to create regions of hydrophilic surface exposing on the bottom. In another embodiment, the mask can be applied after the chemical treatments, creating hydrophilic regions at the top of the nanostructures.

Specifically, the size and density of the exposed hydrophilic regions can be controlled by one or more of the following parameters: the applied voltage of the electrospray, the flow rate of the electrospray, the duration of the electrospray, and the distance from which the spray is applied. Furthermore, the dimension of nanostructures can also be adjusted by changing the parameters of the surface treatment.

In an embodiment, by using a combination of electrospray and surface oxidization technique, a heterogeneous wetting surface comprising microscale hydrophilic regions surrounded by superhydrophobic nanostructures can be fabricated. In general, the hydrophilic regions act as condensing areas by enhancing the water capture ability from moisture, while the global superhydrophobic property enables the condensed droplets to spontaneously jump out of the surface by coalescence at micrometric length scales, on the order of between about 10 μm and about 100 μm . Similar to the homogeneous superhydrophobic surfaces provided herein, the droplets' spontaneous jumping and departure results in smaller average droplet size and improved thermal resistance when compared with conventional hydrophobic surfaces in continuous condensation.

In addition, by providing heterogeneous wetting surfaces in alternate arrangement with flat hydrophilic surfaces comprising metals such as, for example, copper, zinc, aluminum, iron, associated metal oxides thereof, or a combination of all of the above, as the fins employed in an exemplary condenser system, the overall water collection performance can be improved due to efficient collection and removal of the jumping droplets.

The condensation system and methods of making and using same of embodiments of the subject invention offer the following distinct advantages. First, compared with conventional technologies such as photolithography and laser processing, the fabrication strategy of a heterogeneous wetting surface is convenient, scalable, and cost-effective. Second, the geometry of the structures bearing the hydrophilic and superhydrophobic or heterogeneous wetting surface can be easily adapted according to a desired heat exchanging application and condensing environment. Third, the manufacturing process provided can be easily adjusted to accommodate a variety of materials specific to a desired application. Fourth, the fabrication process of the heterogeneous wetting surface does not involve any oils

- 5 or organic solvents that can otherwise limit the surface being employed in systems requiring vacuum applications.

A greater understanding of the present invention and of its many advantages may be had from the following examples, given by way of illustration. The following examples are illustrative of some of the methods, applications, embodiments, and variants of the present invention. They are, of course, not to be considered as limiting the invention. Numerous changes and modifications can be made with respect to the invention.

EXAMPLE 1—Application in a Dehumidifier System

15 Energy efficiency of a dehumidifier highly depends on the overall heat transfer coefficient of the heat exchanger as it is the core component for power consumption. An efficient evaporator in dehumidifier is particularly important for energy saving. The water capturing system provided herein can increase the energy efficiency of an indoor humidity control.

20 By assembling alternate superhydrophobic and hydrophilic surfaces on coil-tubes as condensing fins, the condensation is enhanced by accommodating water droplets to spontaneously depart from the superhydrophobic surface and accumulate on the hydrophilic surface. These jumping droplets then accumulate as liquid films, effectively preventing the water vaporization to atmosphere again. Figures 3A and 3B demonstrate two configurations of the condensing fins. In the configuration shown in Figure 3A, a DC electric field can be applied across the hydrophilic and superhydrophobic plates to further enhance the droplet movement from superhydrophobic surfaces to hydrophilic ones.

EXAMPLE 2—Application in a Dew-Harvesting System

30 Dew forms at night as temperature drops and water vapor in the air condenses on cooler surfaces. A conventional dew collector includes a mesh structure to allow moist air to move through. An impenetrable barrier can reduce the speed of air passing through the collector, thereby slowing the processing of fresh air.

As shown in Figures 4A and 4B, a dew-harvesting mesh structure according to an embodiment of the subject invention can employ the water capture strategy provided herein. The hydrophilic surfaces and the superhydrophobic surfaces are positioned perpendicular to each other within the mesh structure, providing a large surface area for condensation nuclei to form on the condenser surface. Jumping droplets from superhydrophobic surfaces can be

- 5 absorbed by the liquid film already formed on the hydrophilic surfaces. By setting the collector in an appropriate angle, the dew can slide from hydrophilic surfaces to the reservoir.

EXAMPLE 3—Application in a Desalination System

Freshwater can be obtained from seawater during the process of phase change. Water
10 vaporizes as a result of the negative pressure in a vacuum chamber. The water vapor then condenses on a bundle of a large number of thin cooling tubes and the distillate is withdrawn and collected. Fifteen to 20 vacuum chambers with ever-increasing levels of negative pressures are chained together to produce a large quantity of freshwater.

As shown in Figure 5, tubular structures bearing hydrophilic and superhydrophobic
15 surfaces can be arranged in alternate pattern in the bundle design of a desalination system according to an embodiment of the subject invention to enhance the freshwater distillation efficiency. Technology provided herein allows a rapid distillation rate even under a lower sub-cooling condition during the desalination process.

20 EXAMPLE 4—Fabrication of a Heterogeneous Wetting Surface with Hydrophilic Property on the Bottom of the Surface

The synergistic cooperation with hydrophilic micropatches and superhydrophobic nanostructures leads to a liquid wetting feature that allows the transition from filmwise condensation to dropwise condensation during heat transfer process. By patterning the
25 hydrophilic condensing area at the bottom of interfacial structures to form a heterogeneous wetting surface, the condensed liquid can form a partial-Wenzel droplet morphology [7, 8], which promotes the droplet heat transfer through the liquid bridges as shown in Figure 6A. In an embodiment, the heterogeneous wetting surface can be manufactured through a combination of mask pre-spraying and chemical surface treatment.

30 As the common heat transfer material, copper was selected as the substrate for surface fabrication. Surface anodization (*i.e.*, oxidation) in alkaline solution was used to form CuO nanostructures at the interface, a methanol-soluble nylon was accordingly chosen as the mask material due to its alkali resistivity. The nylon-methanol solution was first sprayed onto the copper substrate to form the stochastic masks by using the electrospray technology. An SEM
35 image of a sprayed copper surface is shown in Figure 6B. The size and density of nylon mask can be controlled by adjusting the applied voltage, the solution flow rate, the spraying duration, and the distance from which the solution is sprayed. This mask coating method demonstrates a uniform distribution of droplets.

To characterize the surface morphology, the mask size, density distribution, and area fraction were measured for several different samples. The detailed experiment data of mask electro spraying coating are listed in Table 2 below. To strengthen the mask adhesion to substrate, the nylon mask sprayed on the surface can be heated to 150 °C for approximately 30 minutes. This annealing process leads to the reflow of nylon material and fills the gap between the coating and substrate. This masking technology *via* electro spraying can also be generally applied on other metallic substrates.

Table 2. Nylon mask distributions with different electro spraying parameters

Voltage U (kV)	Flowrate μl (min)	Spraying time t (s)	Distance L (mm)	Average diameter D_{avg} (μm)	Area fraction ϕ
4	0.7	100	105	1.582	0.0644
4	1	100	105	1.633	0.0668
6	0.7	90	105	1.500	0.1071
6	1	90	105	1.723	0.1218

After surface anodization in NaOH solution, the needle-like CuO nanostructures were grown outwards from the areas not covered with the nylon mask (Figure 6C). Then the global superhydrophobic property on whole surface was obtained by using the chemical vapor deposition to functionalize the surface with a perfluoro silane such as, for example $\text{CF}_3(\text{CF}_2)_7\text{CH}_2\text{CH}_2\text{Si}(\text{OCH}_3)_3$ (FAS-17), though other types of hydrophobic molecules can also be used for functionalization as discussed herein. The nylon mask was then completely removed by thoroughly rinsing the surface with methanol, thereby recovering the hydrophilic property at the exposed area where the masks have peeled. The heterogeneous wetting surface provided herein can also be manufactured on other metallic substrates, provided that the nanostructures form outward on the surface. Non-limiting examples of nanostructures include ZnO and Al_2O_3 nanowires.

EXAMPLE 5—Fabrication of a Heterogeneous Wetting Surface with Hydrophilic Property at the Top of the Surface

In highly humid environment, the condensed droplets on a partial-Wenzel wetting surface (*e.g.*, the heterogeneous wettable surface provided herein) are likely to be pinned on

5 the surface because liquid bridges formed can significantly increase the adhesion force that impedes the droplets' departure. By switching the order of mask spraying, surface oxidation, and functionalization, we can form heterogeneous wetting surfaces with hydrophilic property at the top instead of on the bottom.

Following surface oxidation, the nylon mask can be sprayed at the top of the
10 nanostructures to form microscale masks, as shown in Figures 7A and 7B. Then the entire surface was salinization to form superhydrophobic property on nanostructures. The microscale hydrophilic area can be subsequently created after removing the sprayed masks through a methanol rinse. This top-hydrophilic topography not only can enable a recurrent filmwise to dropwise condensation, but can also ensure even droplet suspension under humid
15 conditions [6, 9].

The experimental comparison of condensation dynamics on aluminum-based superhydrophobic and heterogeneous wetting surfaces are presented in Figures 7C and 7D. The combination of multiscale hydrophilic and superhydrophobic structures (*i.e.*, a heterogeneous wetting surface) is shown to enhance the droplet nucleation density as
20 compared to a homogeneous superhydrophobic surface. The rate of spontaneous jumping of droplets was not affected by the hydrophilic condensing area since the size and density of sprayed mask were carefully controlled. The suspended dropwise state on top of surface structures promises enough energy to overcome the pinning force during the droplet coalescence. Therefore, the heterogeneous wetting surface demonstrates the efficient
25 condensation performance by the combinatorial advantages of hydrophilic and superhydrophobic properties.

It should be understood that the examples and embodiments described herein are for illustrative purposes only and that various modifications or changes in light thereof will be
30 suggested to persons skilled in the art and are to be included within the spirit and purview of this application.

All patents, patent applications, provisional applications, and publications referred to or cited herein (including those in the "References" section) are incorporated by reference in
35 their entirety, including all figures and tables, to the extent they are not inconsistent with the explicit teachings of this specification.

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9. Ölçeroğlu, E. and M. McCarthy, *Self-Organization of Microscale Condensate for Delayed Flooding of Nanostructured Superhydrophobic Surfaces*. ACS Applied Materials & Interfaces, 2016. **8**(8): p. 5729-5736.

CLAIMS

What is claimed is:

1. A system of capturing condensed liquid, the system comprising:
a first structure having at least one surface substantially wettable by said liquid; and
a second structure having at least one surface substantially non-wettable by said liquid,

wherein the at least one substantially wettable surface of the first structure is separated from the at least one substantially non-wettable surface of the second structure by a distance in a range of from 1 mm to 15 mm, and

wherein the system is configured such that droplets of said liquid first condense on the at least one substantially non-wettable surface of the second structure, and spontaneously jump off to and accumulate on the at least one substantially wettable surface of the first structure.

2. The system according to claim 1, wherein the liquid is water.

3. The system according to any of claims 1-2, wherein the at least one substantially wettable surface of the first structure is flat.

4. The system according to any of claims 1-3, wherein the at least one substantially wettable surface of the first structure comprises at least one of copper, aluminum, zinc, iron, and associated metal oxides thereof.

5. The system according to any of claims 1-4, wherein the at least one substantially non-wettable surface of the second structure comprises a plurality of three-dimensional nanoscopic hydrophobic structures deposited onto a hydrophilic substrate, and wherein isolated regions of the hydrophilic substrate are exposed through the nanoscopic structures.

6. The system according to any of claims 1-4, wherein the at least one substantially non-wettable surface of the second structure comprises isolated regions of a

hydrophilic substrate disposed atop a plurality of three-dimensional nanoscopic hydrophobic structures.

7. The system according to any of claims 5-6, wherein the three-dimensional nanoscopic structures comprise a metal oxide selected from copper oxide, aluminum oxide, zinc oxide, and a combination thereof.

8. The system according to any of claims 5-7, wherein the hydrophilic substrate comprises at least one of copper, aluminum, zinc, iron, and associated metal oxides thereof.

9. The system according to any of claims 1-8, wherein the at least one substantially wettable surface of the first structure is hydrophilic.

10. The system according to any of claims 1-4, wherein the at least one substantially non-wettable surface of the second structure is superhydrophobic.

11. The system according to any of claims 1-10, wherein each substantially wettable surface of the at least one substantially wettable surface of the first structure is disposed parallel to each substantially non-wettable surface of the at least one substantially non-wettable surface of the second structure.

12. The system according to any of claims 1-10, wherein the at least one substantially wettable surface of the first structure is disposed at an angle with respect to the at least one substantially non-wettable surface of the second structure.

13. The system according to claim 12, wherein each substantially wettable surface of the at least one substantially wettable surface of the first structure is perpendicular to each substantially non-wettable surface of the at least one substantially non-wettable surface of the second structure.

14. The system according to claim 12, wherein the at least one substantially wettable surface of the first structure is disposed at an acute angle with the at least one substantially non-wettable surface of the second structure.

15. The system according to any of claims 1-14, wherein the first structure and the second structure have the same geometry.

16. The system according to any of claims 1-14, wherein the first structure and the second structure have different geometries.

17. A system of capturing condensed liquid, the system comprising:
a first structure having at least one hydrophilic surface, wherein the hydrophilic surface is flat; and

a second structure having at least one hydrophobic surface, wherein the hydrophobic surface comprises a plurality of three-dimensional nanoscopic structures on top of and substantially covering the surface,

wherein the at least one hydrophilic surface of the first structure is separated from the at least one hydrophobic surface of the second structure by a distance in a range of from 1 mm to 15 mm, and

wherein the system is configured such that water droplets first condense on the at least one hydrophobic surface of the second structure, and spontaneously jump off to and accumulate onto the at least one hydrophilic surface of the first structure.

18. A system of capturing condensed liquid, the system comprising:
a first structure having at least one hydrophilic surface, wherein the hydrophilic surface is flat; and

a second structure having at least one heterogeneous wetting surface, wherein the at least one heterogeneous wetting surface comprises a plurality of regions of a hydrophilic substrate dispersed among a plurality of three-dimensional nanoscopic hydrophobic structures,

wherein the at least one hydrophilic surface of the first structure is separated from the at least one heterogeneous wettable surface of the second structure by a distance in a range of from 1 mm to 15 mm, and

wherein the system is configured such that water droplets first condense on the at least one heterogeneous wetting surface of the second structure, and spontaneously jump off to and accumulate onto the at least one substantially hydrophilic surface of the first structure.

19. The system according to any of claims 1-18, wherein the system is applied in a device capable of transferring heat by condensation of water.

20. The system according to claim 19, wherein the device is selected from a dehumidifier, a heating ventilation air conditioning (HVAC) system, a food storage unit, a desalination system, a dew-harvesting collector, and a combination thereof.

21. The system according to any of claims 1-18, wherein the system is applied in a water collection device.

22. A method of capturing condensed liquid, comprising:

providing the system according to any of claims 1-21;

allowing a plurality of droplets of said liquid condense on the at least one substantially non-wettable surface of the second structure, wherein said droplets spontaneously depart from the at least one substantially non-wettable surface of the second structure when they have grown to an energetically favorable size; and

allowing said droplets to accumulate onto the at least one substantially wettable surface of the first structure,

wherein the at least one substantially wettable surface of the first structure is separated from the at least one substantially non-wettable surface of the second structure by a distance suitable for accommodating the spontaneous departure of the plurality of said droplets from the second structure and the accumulation thereof on the first structure.

24. The method according to claim 22, wherein the energetically favorable size is between 10 μm and 100 μm .

25. A method of fabricating a heterogeneous wetting surface, the method comprising:

providing a hydrophilic substrate;

electrospraying a layer of alkaline-resistant solution onto the hydrophilic substrate to form a mask, presenting a plurality of regions exposing the underlying substrate;

applying a current in the presence of an alkaline solution with the masked substrate as the anode;

allowing three-dimensional nanoscopic structures to grow through the plurality of exposed regions of the underlying substrate;

functionalizing the surface with a substantially hydrophobic substance;

rinsing the surface with a polar solvent; and

removing the mask.

26. The method according to claim 25, wherein the size and density of the mask is determined by at least one of the following factors: applied voltage of the electrospray; the flow rate of the electrospray; the duration of the electrospray; and the distance from which the electrospray is applied.

27. The method according to any of claims 25-26, wherein the hydrophilic substrate is annealed to 150° C prior to the electrospray process.

28. The method according to any of claims 25-27, wherein the alkaline solution comprises at least one of sodium oxide, potassium oxide, calcium oxide, and magnesium oxide.

29. The method according to any of claims 25-28, wherein the polar solvent used to rinse the functionalized surface is an alcohol.

30. The method according to claim 29, the polar solvent is methanol.

31. The method according to any of claims 25-30, wherein the alkaline-resistant solution is a polyamide dissolved in a polar solvent.

32. The method according to claim 31, wherein the solution is nylon dissolved in methanol.

33. The method according to any of claims 25-32, wherein the substantially hydrophobic substance is a silane.

34. The method according to any of claims 25-33, wherein the silane is a perfluoro silane.

35. A method of fabricating a heterogeneous wetting surface, comprising:
providing a hydrophilic substrate;
applying a current in the presence of an alkaline solution with the masked substrate as the anode;
allowing three-dimensional nanoscopic structures to grow on and substantially cover the underlying substrate;
functionalizing the nanoscopic structures with a hydrophobic substance;
electrospraying a layer of alkaline-resistant solution onto the functionalized nanoscopic structures form a mask, presenting a plurality of regions exposing the nanoscopic structures;
rinsing the surface with a polar solvent; and
removing the mask.

36. The method according to claim 35, wherein the size and density of the mask is determined by at least one of the following factors: applied voltage of the electrospray, the flow rate of the electrospray, the duration of the electrospray, and the distance from which the electrospray is applied.

37. The method according to any of claims 35-36, wherein the alkaline solution comprises at least one of sodium oxide, potassium oxide, calcium oxide, and magnesium oxide.

38. The method according to any of claims 35-37, wherein the polar solvent used to rinse the surface is an alcohol.

39. The method according to claim 38, the polar solvent is methanol.

40. The method according to any of claims 35-39, wherein the alkaline-resistant solution is a polyamide dissolved in a polar solvent.

41. The method according to claim 40, wherein the solution is nylon dissolved in methanol.

42. The method according to any of claims 35-41, wherein the substantially hydrophobic substance is a silane.

43. The method according to claim 42, wherein the silane is a perfluoro silane.

44. The system according to any of claims 1-21, wherein the at least one substantially wettable surface of the first structure is separated from the at least one substantially non-wettable surface of the second structure by a distance in a range of from 2 mm to 6 mm.

45. The system according to claim 44, wherein the at least one substantially wettable surface of the first structure is separated from the at least one substantially non-wettable surface of the second structure by a distance in a range of from 3 mm to 5mm.

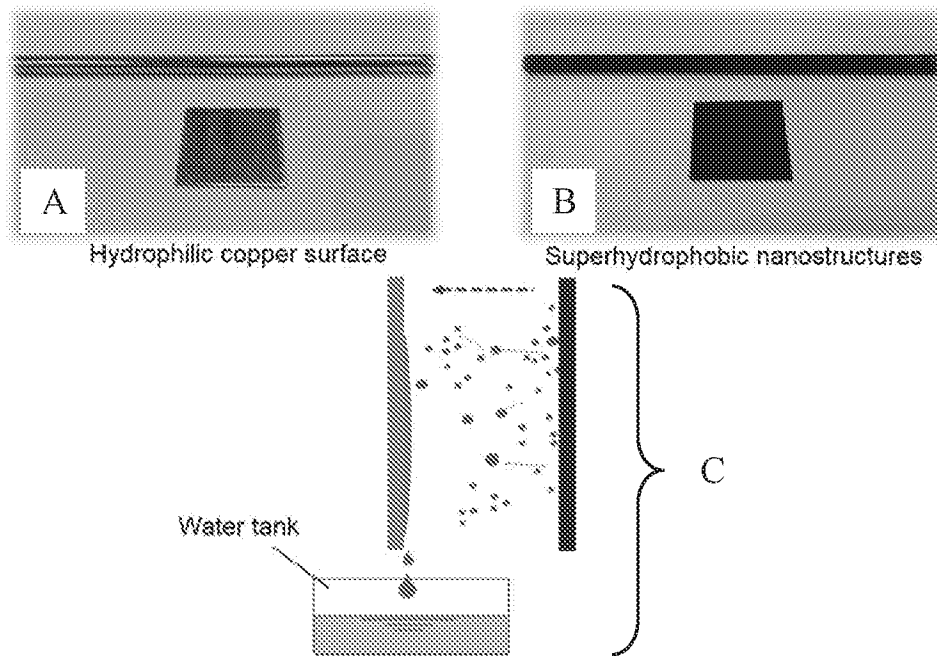


FIG. 1

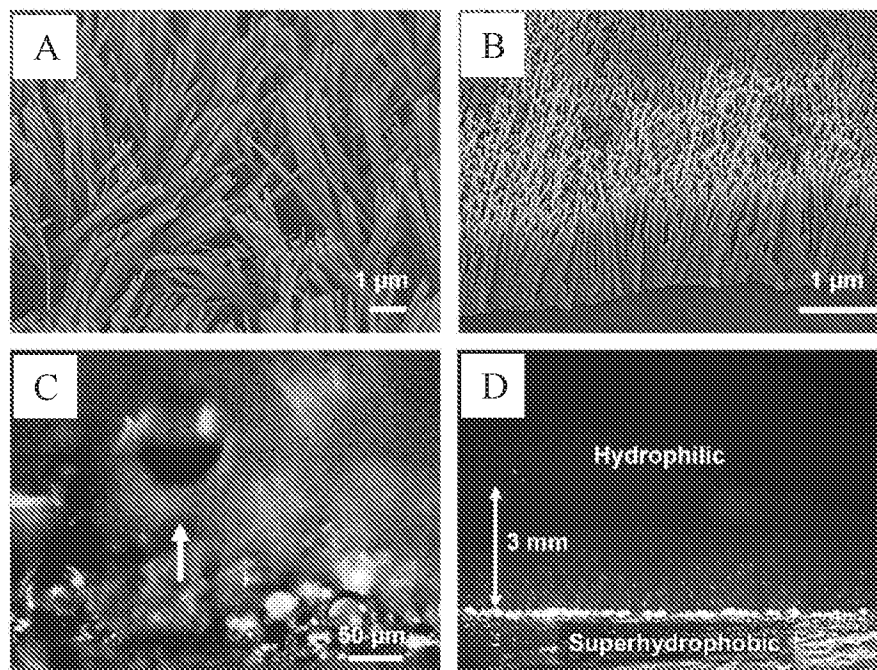


FIG. 2

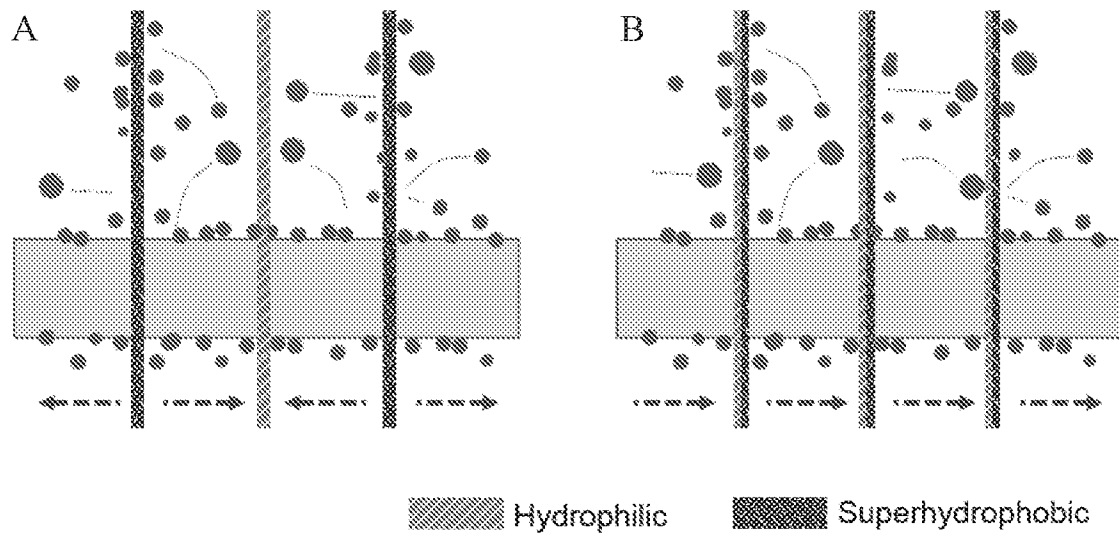


FIG. 3

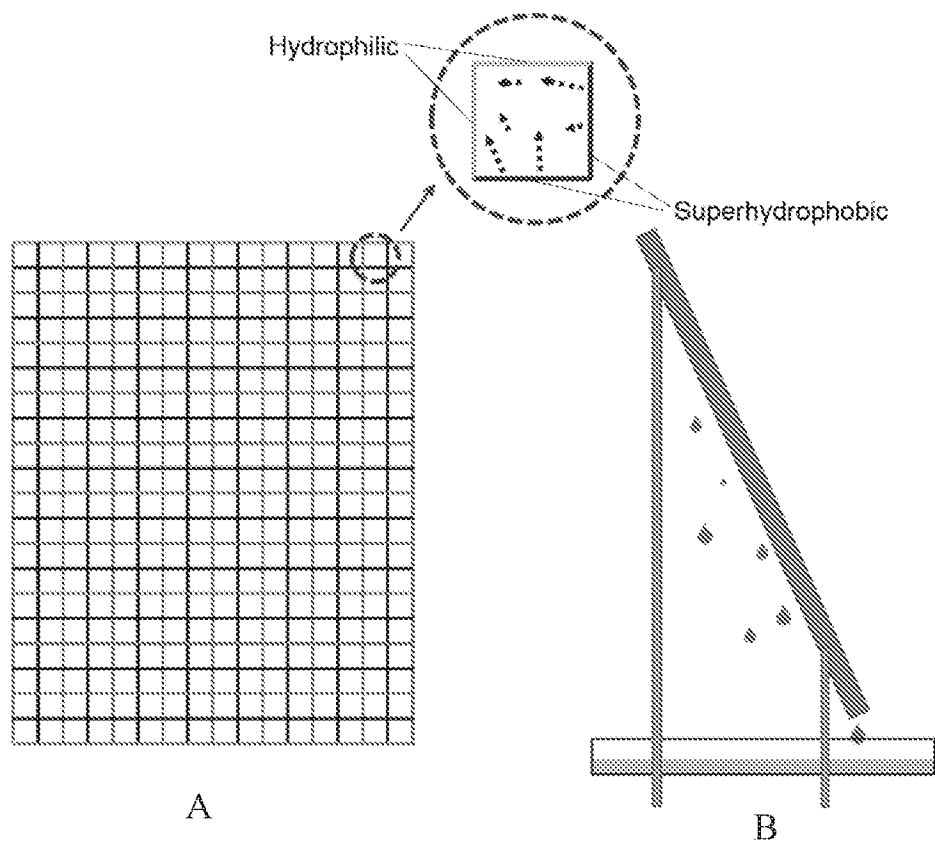


FIG. 4

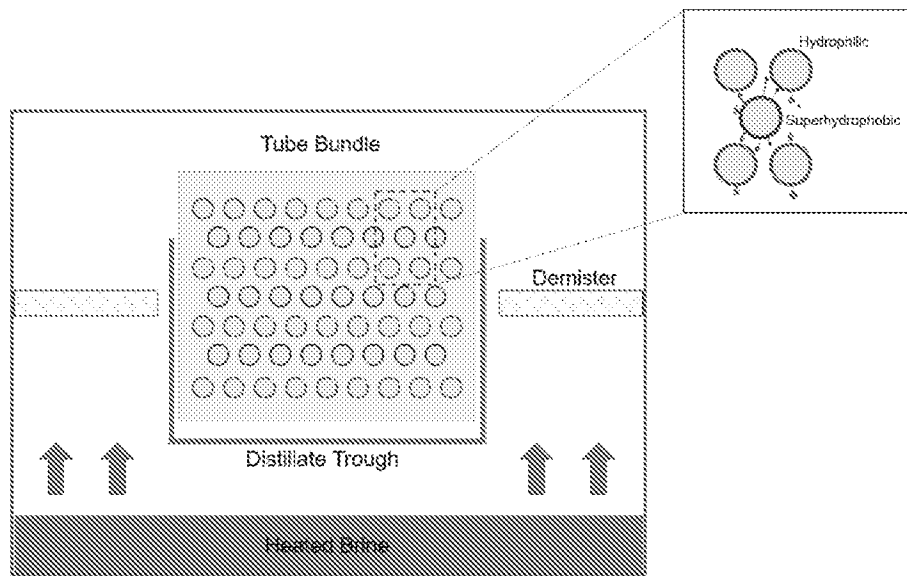


FIG. 5

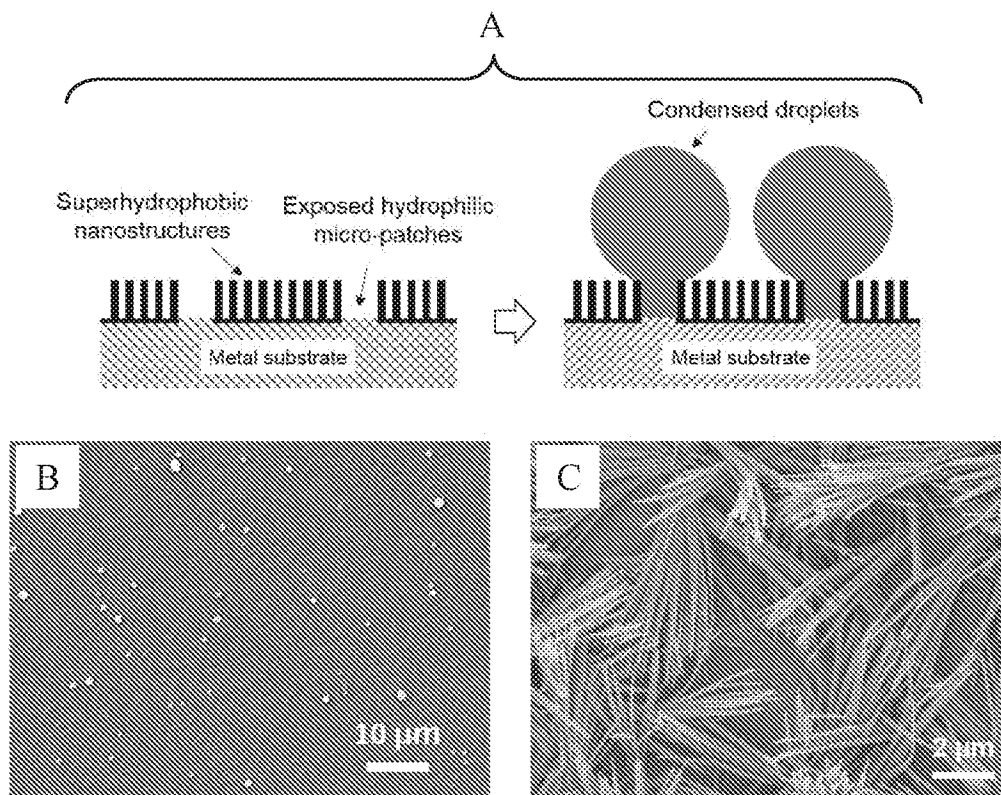


FIG. 6

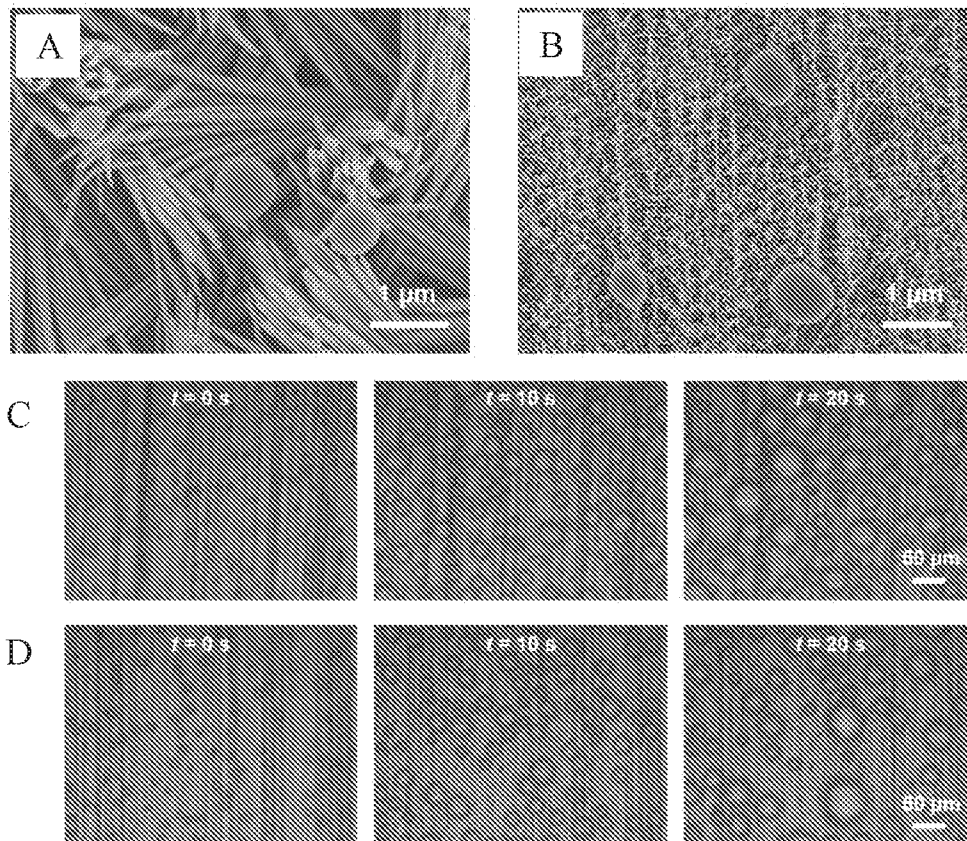


FIG. 7

INTERNATIONAL SEARCH REPORT

International application No.

PCT/IB2017/000370

A. CLASSIFICATION OF SUBJECT MATTER

F28F 17/00(2006.01)i; F24F 13/00(2006.01)i; F28B 1/00(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

F28F; F24F; F28B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

CNABS,CNTXT,USTXT,EPTXT,JPABS,DWPI,SIPOABS: SHUHUAI YAO,water captur+,water collector,heater,transfer, hydrophobic, hydrophilic, wettable, non?wetable, metal, heterogeneous,nano, electro?spray+, function+, nylon,cu,al,zn, fe, copper, aluminium, zinc, iron, superhydrophobic, silane, polyamide

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 2119996 A1 (KOBE SEIKO SHO K.K. ET AL.) 18 November 2009 (2009-11-18) page 2 paragraph[0003], paragraph[0010], page 6 paragraph[0043], claims 1-2, figure 1	1-22, 24-45
A	CN 102884391 A (MITSUBISHI ELECTRIC CORP.) 16 January 2013 (2013-01-16) claims 1-10, figures 1-19	1-22, 24-45
A	CN 1477366 A (LG ELECTRONICS INC.) 25 February 2004 (2004-02-25) claims 1-5, figures 1-6	1-22, 24-45
A	DE 20001146 U1 (YANG FAN DEV.CO., LTD.) 31 May 2000 (2000-05-31) claims 1-8, figures 1-3	1-22, 24-45
A	Benli Peng et al. "Experimental investigation on steam condensation heat transfer enhancement with vertically patterned hydrophobic-hydrophilic hybrid surfaces" <i>International Journal of Heat and Mass Transfer</i> , Vol. 83, 12 December 2014 (2014-12-12), ISSN: 0017-9310, the whole document	1-22, 24-45
A	EP 2413085 A1 (KOBE SEIKO SHO K.K. ET AL.) 01 February 2012 (2012-02-01) claims 1-6	1-22, 24-45

☐ Further documents are listed in the continuation of Box C.☒ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

29 June 2017

Date of mailing of the international search report

20 July 2017

Name and mailing address of the ISA/CN

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INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.

PCT/IB2017/000370

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				CN	101568793	A	28 October 2009
				EP	2119996	B1	29 June 2016
				CN	101568793	B	15 February 2012
				MY	147891	A	31 January 2013
				AU	2008215475	B2	28 April 2011
				WO	2008099868	A1	21 August 2008
				AU	2008215475	A1	25 June 2009
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				JP	2004085169	A	18 March 2004
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				WO	2010110332	A1	30 September 2010
				JP	2010223514	A	07 October 2010