



(51) International Patent Classification:

C08G 12/30 (2006.01)

(21) International Application Number:

PCT/IN2019/050078

(22) International Filing Date:

02 February 2019 (02.02.2019)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

201741039127 02 February 2018 (02.02.2018) IN

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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, JO, 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).

Declarations under Rule 4.17:

— of inventorship (Rule 4.17(iv))

(54) Title: A MODIFIED SURFACE FOR CONDENSATION

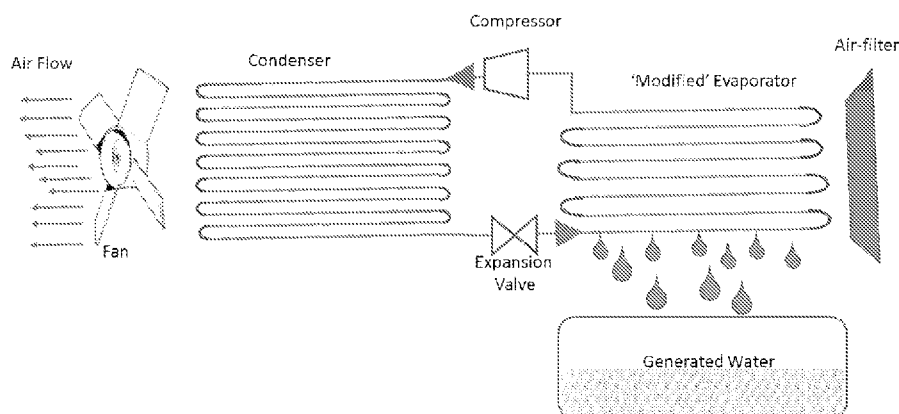


FIGURE 1

(57) Abstract: The present invention relates to a method of enhancing heat transfer of metallic surfaces by (1) fabricating hierarchical micro-nanostructured surfaces using etching processes, and (2) fabricating hydrophobic and hydrophilic regions, using a printing or a coating technique, followed by etching. The said method enhances the density of condensation sites over a metallic surface and additionally facilitates the departure of condensed droplets from the surface. Such a surface also enhances the sensible heat transfer characteristics, and improves the coefficient of performance (COP) of refrigeration systems for applications like atmospheric water generators, dehumidifiers, air conditioners, etc.



Published:

- *with international search report (Art. 21(3))*
- *in black and white; the international application as filed contained color or greyscale and is available for download from PATENTSCOPE*

DESCRIPTION

TITLE OF THE INVENTION

5 A MODIFIED SURFACE FOR CONDENSATION

FIELD OF THE INVENTION

The present invention relates to a method of creating a modified surface for condensation.
10 More specifically, it relates to the fabrication of hierarchical micro-nanostructures with/ without local wettability gradients, over metal, prepared by etching and/or patterning processes in order to improve the efficiency of condensation heat transfer. Further, hierarchical structures, with/without wettability gradients also improve the sensible heat transfer.

15 BACKGROUND OF THE INVENTION

Heat transfer plays a crucial role in heating and air conditioning industries. Phase change is essential to energy applications, where it drastically enhances heat transfer because latent heat is typically much larger than sensible heat. Researchers have demonstrated the ability to enhance
20 phase change heat transfer across surfaces by surface engineering at micro- and nano- length scales.

The present invention relates to a method of creating a modified surface for energy-efficient condensation. It also offers an additional advantage of improving the sensible heat transfer.

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SUMMARY OF THE INVENTION

The present invention relates to a method of creating a modified surface for condensation. More specifically, relates to a modified surface for condensation, wherein the said surface
30 comprises of scalable hierarchical micro-nanostructures includes aluminium surface which consist of scalable hierarchical $\text{AlOOH}/\text{Al}_2\text{O}_3$ micro-nanostructures and hydrophobic-hydrophilic patterned regions for increasing the rate of condensation of fog, humidity and water vapor. The fabrication of hierarchical micro-nanostructures over a metallic surface, preferably

copper, more preferably aluminum, prepared by etching process in order to improve its efficiency of condensation, preferably of atmospheric water.

In one embodiment, the present invention relates to a method of fabricating hierarchical micro-nanostructures using an etching process which creates large number of such droplet nucleation sites across the surface, resulting in an enhanced rate of condensation. The hierarchical structures comprise of micron-cones of height ranging from 10-20 μm , covered with nanoscale bumps of nearly 500 nm height. For the etching process, mild basic medium including dilute NaOH, KOH etc. is used or a mildly acidic medium of dilute FeCl_3 , H_2O_2 , HF, HCl, etc. is used.

In other embodiment, the present invention relates to a method of fabricating hydrophobic and hydrophilic regions by printing or coating an etch-resistant hydrophobic ink on the metal surface and etching the non-printed regions using acidic and/or basic medium to render them hydrophilic. Creating such patterns enables localization of micro-nanostructures to specific regions, which improves the rate of departure of condensed droplets from the surface, thus improving the overall rate of water collection.

The modified surfaces also improve sensible heat transfer between metallic surfaces and ambient air, thus improving heat transfer characteristics of heat exchangers and coefficient of performance (COP) of corresponding refrigeration systems, dehumidifiers, air conditioners, cooling towers, or preferably atmospheric water generators.

BRIEF DESCRIPTION OF THE DRAWINGS:

Figure 1 Schematic of an atmospheric water generator. Ambient air enters the system by passing through an air-filter (extreme right) and then passes across the 'modified' evaporator having fins with hierarchical micro-nanostructures, over which condensation takes place. Cold air after the evaporator then passes across the hot condenser and leaves the system thereafter.

Figure 2 SEM image of the aluminium fin surface, on which hierarchical micro-nanostructures were created by mild etching process. The micro-cones are covered with nano-bumps. These structures were reproduced on the surface of evaporator and condenser fins.

Figure 3 Schematic representation of a hydrophobic-hydrophilic patterned metal surface using screen printing followed by etching. The black region is a screen-printed etch-resistant hydrophobic coating (2) Etching performed after printing renders star-shaped regions

hydrophilic due to creation of hierarchical micro-nanostructures (1) and the remaining un-etched region hydrophobic. The scale indicated in the figure is approximate, and may vary, depending upon the coating.

Figure 4 SEM image of hydrophobic-hydrophilic patterned surface with micro-nano structures

Referring to the drawings, the embodiments of the present invention are further described. The figures are not necessarily drawn to scale, and in some instances the drawings have been exaggerated or simplified for illustrative purposes only. One of ordinary skill in the art may appreciate the many possible applications and variations of the present invention based on the following examples of possible embodiments of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

As required, detailed embodiments of the present invention are disclosed herein; however, it is to be understood that the disclosed embodiments are merely exemplary of the invention that may be embodied in various forms. The figures are not necessarily to scale; some features may be exaggerated to show details of particular components. Therefore, specific structural and functional details disclosed herein are not to be interpreted as limiting, but merely as a basis for the claims and as a representative basis for teaching one skilled in the art to variously employ the present invention.

The present invention relates to a method of creating a modified surface for condensation. More specifically, relates to a modified surface for condensation, wherein the said surface comprises of scalable hierarchical micro-nanostructures includes aluminium surface which consist of scalable hierarchical $\text{AlOOH}/\text{Al}_2\text{O}_3$ micro-nanostructures and hydrophobic-hydrophilic patterned regions for increasing the rate of condensation of fog, humidity and water vapor.

The present invention relates to a method of fabricating hierarchical micro-nanostructures on metal surface using an etching process which enhances the number of condensation sites over a surface, improving the rate of condensation of humidity. The hierarchically-structured surface comprises of micron-sized conical structures of height nearly in the range of 10-20 μm , entirely covered by nano-scale bumps of nearly 500 nm height. Hierarchical micro-nanostructure also generate turbulence in air stream, which increases sensible heat transfer of the heat exchanger

coil. For etching process, mild basic medium such as dilute NaOH, KOH etc. or a mild acidic medium such as FeCl_3 , H_2O_2 , HF, HCl, etc. is used.

The method of fabricating hydrophobic and hydrophilic regions includes printing or coating of an etch-resistant hydrophobic ink on the metal surface and etching the non-printed regions using acidic and/or basic medium to render them hydrophilic. The superhydrophobic area will facilitate the departure of condensed droplets from the surface. The etch-resistant hydrophobic ink is coated on the metal surface preferably by spray coating or screen printing. Wherein, etch-resistant hydrophobic ink is a thermally conducting carbon-based ink, preferably graphite/graphene based ink.

The modified surface with enhanced rate of condensation was tested against a commercial heat exchanger coil for heat transfer characteristics. The test setup design was same as the atmospheric water generator design, shown in figure 1. Figure 1 shows that an atmospheric water generator where an ambient air enters the system by passing through an air-filter (extreme right) and then across the 'modified' evaporator having micro-nanostructured fin surfaces over which condensation takes place. Cold air after the evaporator then passes across the hot condenser and leaves the system thereafter. Modified heat exchanger coil reflected in a 2-14.5% improvement in the coefficient of performance (COP) of the refrigeration system, compared to the same system with a standard heat exchanger coil.

Hierarchical micro-nanostructures comprise of micron-sized cones, covered by nano-bumps (Figure 2). Hierarchical micro-nanostructures created over the aluminium surface by mild etching process. The micro-cones are covered with nano-bumps. These structures were reproduced on the surface of evaporator and condenser fins. The presence of these micro-cones drastically enhances the number of nucleation sites onto a metal surface, and the nanostructured bumps allow the nucleated droplets to grow and enter into a Cassie-Baxter or a partial-wetting state, thus preventing strong adhesion to the surface. This enables coalescence and movement of the droplets over the surface and prevents flooding of droplets over the entire surface at high condensation rates, thus preventing film formation, which can act as a barrier to any further condensation, resulting in poor rate of condensation.

Performance of the surface have been tested to verify the following characteristics

1. Improvement in rate of condensation, and subsequently water collection because of micro-nanostructures (Table 1),

2. Further improvement in rate of condensation by introducing wettability gradients combined with micro-nanostructures (Table 2).

3. Improvement in COP of the refrigeration cycle with 'modified' evaporator and energy-efficient water collection from such a system (Table 3).

5 4. Improvement in sensible heat transfer at the condenser side due to hierarchical micro-nanostructures present on the surface of the fins (Table 4)

Test 1 Water collection performance comparison of flat aluminum surface against a modified micro-nanostructured aluminum surface (surfaces tested at evaporator-scale)

10 As shown in table 1, compared to a flat aluminum surface, micro-nanostructured surface showed a 30% - 35% improvement in water collection performance under similar ambient conditions (at ~ 26°C dew point).

Table 1 Performance comparison of modified evaporator and a commercial evaporator from a 100-liter per day atmospheric water generator machine, under similar ambient conditions

Commercial Evaporator Performance						
S.No	Temp (°C)	%RH	DPT(°C)	Runtime (hours)	Water Collection (liters)	Liters/Day (LPD)
1	28.0	92	26.6	11.3	49.3	104.7
2	30.5	78	26.2	9.3	35.7	92.0
Modified Evaporator Performance						
3	29.4	82	26	2	10.6	127.2
4	29.2	81	25.6	12.4	66.8	129.3

15 The above results in table 1 demonstrate the capability of micro-nanostructures in enhancing the water collection performance of a flat metal surface. Such structures created over an evaporator, will boost the performance of a dehumidifier, an air conditioner and an atmospheric water generator by improving condensation heat transfer. This will reduce the operating costs and improve the operational power efficiency of an atmospheric water generator
20 by 15- 30 %.

Test 2: Water collection performance comparison between micro-nanostructured surface and the patterned surface with localized micro-nanostructures combined with wettability gradients (surface area = 16 cm²)

In order to further improve the water collection, the droplets were forced to move over the surface at much smaller sizes, at which gravity has an insignificant contribution. This was achieved by patterning the surface into hydrophobic and hydrophilic regions, as shown in Figure 3. Figure 3 illustrates hydrophobic-hydrophilic patterned surface with micro-nano structures within the star-shaped regions. Fabrication process involves creating star-patterns by printing or coating, followed by etching within the star-shaped regions. These structures further increase the rate of water transport away from the surface. These patterns drive water droplets to move spontaneously towards the hydrophilic regions due to the wettability gradients. Subsequently, droplet coalescence occurs in the hydrophilic regions until they are saturated, and gravity causes this locally collected water to drip down from the surface. For this, a screen-printable hydrophobic graphite/graphene coating was used, to create a negative of an array of star-shaped patterns with bare metal surface.

Hydrophobic-hydrophilic patterned surface with micro-nano structures, prepared from the above method, was maintained at a constant temperature below the dew point, and tested for water collection against the etched surface shown in Figure 2. Table 2 compares the water generation performances of surfaces prepared from both the methods.

Table 2 Comparison of water generation performance of micro-nano structured metal surface (S1) versus a hydrophobic-hydrophilic patterned surface with micro-nano structure (S2)

Surface		Surface Area (cm ²)	Cooling method	Heat transfer on hot side	Power input to peltier (W)	Ambient conditions	Water Collected		Water Collected (LPD/m ²)
							Vol. (ml)	Time(h)	
S1	Test 1	16	Peltier module (4 cm x 4 cm) $T_h = T_a$ $T_c = 8.0^\circ\text{C}$	12V DC fan	5.88 W (3.92 V, 1.50A)	24.0°C, 70% RH	13.34	16.6	12.04

S2		16	Peltier module (4 cm x 4 cm) $T_h = T_a$ $T_c = 8.0^\circ\text{C}$	12V DC fan	7.17 W (4.0 V, 1.77A)		17.0 5	16.6	15.4
S1	Test 2	16	Peltier module (4 cm x 4 cm) $T_h = T_a$ $T_c = 8.0^\circ\text{C}$	12V DC fan	5.88 W (3.92 V, 1.50A)	24.5°C, 78% RH	20.9	24.0	13.1
S2		16	Peltier module (4 cm x 4 cm) $T_h = T_a$ $T_c = 8.0^\circ\text{C}$	12V DC fan	7.17 W (4.0 V, 1.77A)		27.8	24.0	17.4

It is therefore conclusive from table 2 that a patterned and subsequently etched surface provides nearly 1.15 – 1.30 times higher water collection performance than a hierarchical micro-nanostructured surface.

5 Test 3: Effect of micro-nanostructures on the Coefficient of Performance (CoP) and energy efficiency of collected water for refrigeration systems by reproducing these structures on the evaporator and condenser

10 A more accurate comparison as well as impact of micro-nanostructures on refrigeration-based AWG machines is evident from Table 3 where heat exchanger-scale surfaces are compared against power efficiency (kWh/liter) and refrigeration system efficiency of the AWG machine. Both surfaces were tested with same refrigeration system, not necessarily optimized to best performance, but under same ambient conditions.

15 **Table 3** Performance comparison between commercial evaporator (Normal) and modified evaporator (modified) with hierarchical micro-nanostructures, in terms of refrigeration system's Coefficient of Performance (CoP) and energy efficiency of an atmospheric water generator. 'Normal' indicates un-modified coil with flat fins, while 'Modified' indicates coil with micro-nanostructured fins

S.No	Date	Ambient		Evaporator used	Condenser used	COP	kWh/ltrs
		T	RH				
1	24-07-2018	36	39	Modified	Normal	3.881	0.625
	11-06-2018	36	39	Normal	Normal	3.769	0.737
2	24-07-2018	31	70	Modified	Normal	3.455	0.438
	23-06-2018	31	70	Normal	Normal	3.383	0.526
3	26-01-2019	31	64	Modified	Modified	5.704	0.482
	29-01-2019	31	69	Normal	Modified	5.593	0.550

Test4:Heat transfer performance of a normal condenser tested against a modified condenser having same micro-nanostructures as the evaporator.

Table 4 Increase in sub-cooling from modified condenser coil

Types of coils used	S.No	Ambient		Pressure	Temperature		
		Temp	RH	Discharge	Tcond out	Tsat	Degree of sub-cooling
		°C	%	Psig	°C	°C	°C
Modified Condenser	1	28	71	265	40	44.02	4.02
	2	29	68	260	39.2	43.27	4.07
	3	31	62	270	40.7	44.77	4.07
Normal Condenser	1	28	72	262	42.6	43.57	0.97
	2	29	72	260	42.8	43.27	0.47
	3	31	69	269	44	44.62	0.62

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Table 4 shows increase in sub-cooling of a standard condenser coil when it is modified to have micro-nanostructures. By modifying heat exchanger /condenser coil, sub-cooling increases to 4 °C, against a 1 °C for a standard heat exchanger/condenser coil at similar ambient and

refrigeration conditions. This further reduces suction to discharge pressure ratio for the compressor, thereby reducing the operational power consumption. Hence improvement in sub-cooling and super-heating of condenser and evaporator coils, respectively, are observed because of the hierarchical micro-nanostructures created over the fin surfaces of the coils.

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It may be appreciated by those skilled in the art that the drawings, examples and detailed description herein are to be regarded in an illustrative rather than a restrictive manner.

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WE CLAIM:

1. A modified metal surface for condensation of fog, humidity and water vapor comprising scalable hierarchical micro-nanostructures, wherein the said metal is aluminium and scalable hierarchical micro-nanostructures are made of $\text{AlOOH}/\text{Al}_2\text{O}_3$.
2. A modified metal surface for condensation of water vapor comprising scalable hierarchical micro-nanostructures and hydrophobic-hydrophilic patterned regions for increasing the rate of condensation of fog, humidity and water vapor, wherein the said metal is aluminium and scalable hierarchical micro-nanostructures are made of $\text{AlOOH}/\text{Al}_2\text{O}_3$.
3. The modified metal surface as claimed in claims 1 and 2, wherein the scalable hierarchical $\text{AlOOH}/\text{Al}_2\text{O}_3$ micro-nanostructures comprise of micron-sized cones with nanostructured bumps, as nucleation sites for droplets.
4. The modified metal surface as claimed in claim 3, wherein the micron-sized conical structure is 10-20 μm in height and completely covered with nano-bumps of nearly 500 nm height.
5. The modified metal surface as claimed in claims 1-4, wherein the scalable hierarchical $\text{AlOOH}/\text{Al}_2\text{O}_3$ micro-nanostructures are prepared by etching process.
6. The modified metal surface as claimed in claims 1-5, wherein the metal surface is etched in a mild basic medium selected from dilute NaOH , KOH or a mild acidic medium selected from dilute FeCl_3 , atmospheric H_2O_2 , HF , HCl .
7. The modified metal surface as claimed in claims 1-6, wherein the etching process involves soft chemistry using solution selected from glucose, sugars and amino acids.
8. The modified metal surface as claimed in claim 2, wherein the hydrophilic-hydrophobic patterned regions are created by a coating or a printing technique including screen printing and spray coating.
9. The modified metal surface as claimed in claim 8, wherein the ink used in printing or coating technique is graphenic /graphitic ink which are etch-resistant, hydrophobic, thermally conducting, and coatable or printable on a metallic surface.
10. The modified metal surface as claimed in claims 1 and 2, wherein the surface improves heat transfer efficiency of heat exchanger coils for applications in heating, air conditioning and used for condensation and water collection for atmospheric water generators.

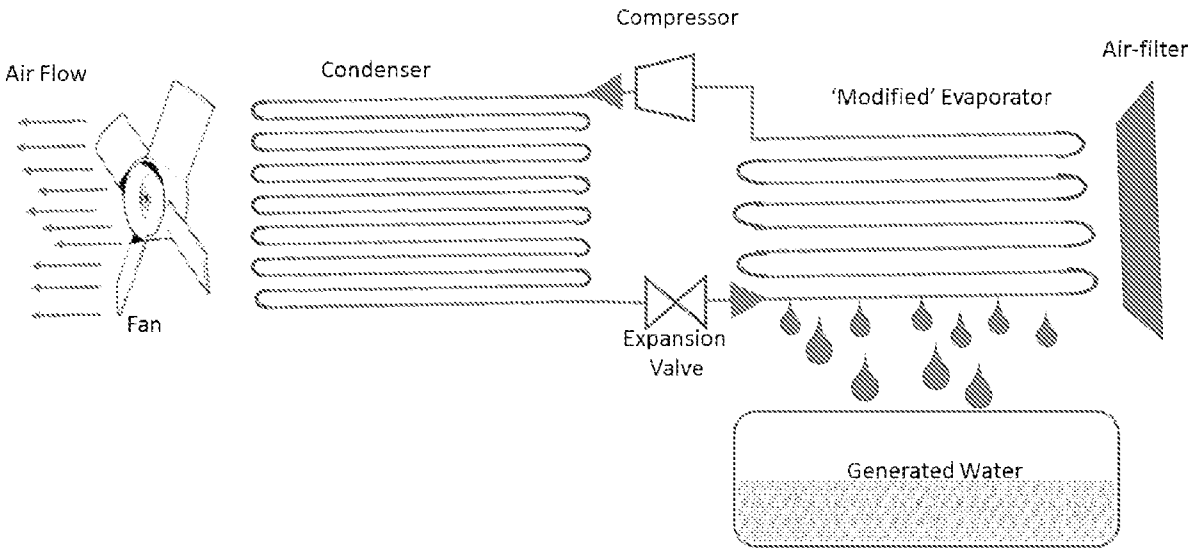
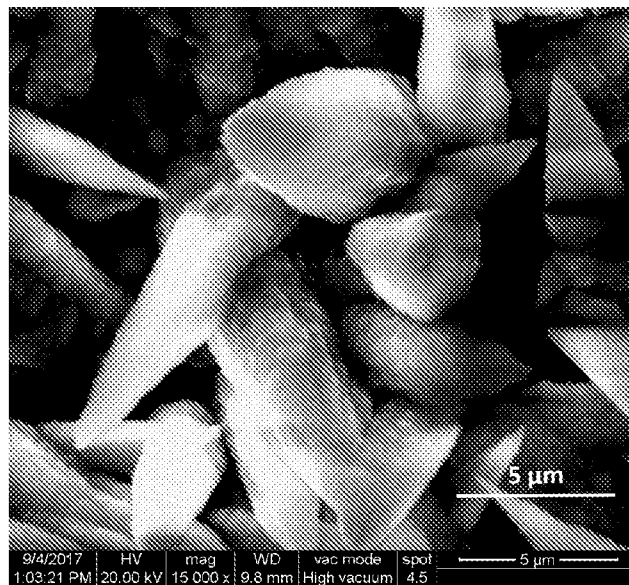


FIGURE 1

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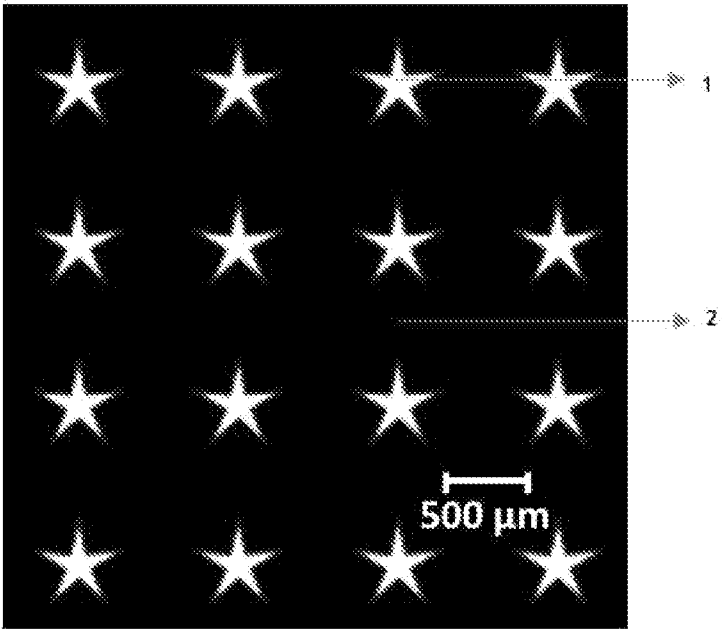
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FIGURE 2

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FIGURE 3

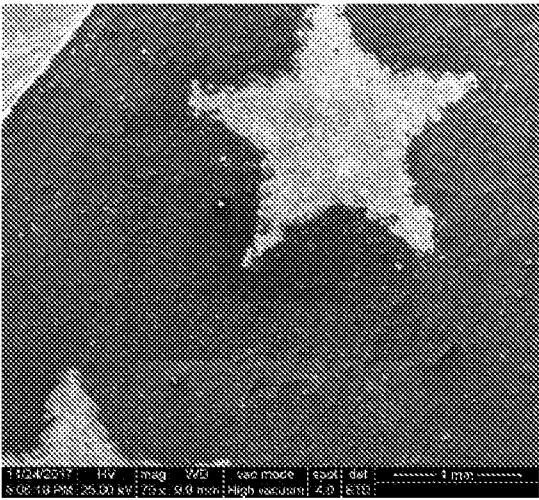
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FIGURE 4

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/IN2019/050078

A. CLASSIFICATION OF SUBJECT MATTER
C08G12/30 Version=2019.01

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)

C08G

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)

TotalPatent One, IPO Internal Database

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	Zhang, Songnan, et al. "Bioinspired special wettability surfaces: From fundamental research to water harvesting applications." Small 13.3 (2017): 1602992. (2016-12-09) https://doi.org/10.1002/smll.201602992 abstract, page 22 last paragraph lines 4-8, figure 3 and 16-17	1-10

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

* Special categories of cited documents:	"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
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Date of the actual completion of the international search

16-05-2019

Date of mailing of the international search report

16-05-2019

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