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研究課題名（和文）Effect of Micro-/Nano-patterned Wettability on the Fundamentals of Condensation Heat Transfer

研究課題名（英文）Effect of Micro-/Nano-patterned Wettability on the Fundamentals of Condensation Heat Transfer

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研究成果の概要（和文）：凝縮液滴直下の表面の構造と濡れ性は凝縮の動力学と伝熱性能に決定的な影響を与えることが分かった．以下の事項が明らかになった． 1．濡れ性をパターン化したマイクロ構造表面では，マイクロピラーの撥水側面から頂上の親水領域へ液滴が移動することを示した． 2．完全な親水性マイクロ構造表面において滴状凝縮と膜状凝縮が同時に生じることを初めて示した． 3．ミクロンサイズの液滴のJumping droplet現象はマイクロ構造の存在によって抑制される． 4．霧の捕集性能はグラジオラス化の花(Gladiolus Dalenii)のユニークなマイクロ・ナノ構造を包含した構造によって促進することができる．

研究成果の概要（英文）：The physical binary interactions between liquids and solid surfaces that combine micro- and nano-features and different wettability during condensation phase-change is further investigated here. The surface structure and its intrinsic wettability underneath condensing droplets are found to play a crucial role during the dynamics of condensation and on the heat transfer performance. We elucidated: 1. On a patterned wettability microstructured surface the droplet migration from the hydrophobic side of a micropillar to its hydrophilic top was demonstrated. 2. A simultaneous dropwise and filmwise condensation on a completely hydrophilic microstructured surface is reported for the first time. 3. The suppression of the droplet-jumping performance of micrometer droplets is induced in the presence of microstructures. 4. Fog harvesting performance is enhanced by the inclusion of the unique micro- and nano-structures of the Gladiolus Dalenii biological sample.

研究分野： Mechanical Engineering, Thermal Engineering

キーワード： Simult Dropwise Filmwise　Thermofluid Heat Transf　Superhydrophobic　Surface Structure　Micro structures　Angular Deviation　Droplet-Jumping　Coating Stability

１．研究開始当初の背景

Dropwise Condensation (DWC) heat transfer can achieve one order of magnitude greater heat transfer rates than Filmwise Condensation (FC) [Umur, A., Griffith, P., J. Heat Transf. 87(2), pp. 275, 1965]. For high efficient DWC, the continuous nucleation, growth and self-detachment of small droplets is necessary. Current research focus mainly on the use of superhydrophobic surfaces, i.e., low CAH surfaces, for the enhancement of drop self-detachment [Boreyko et al., PRL 103, 184501, 2009 & Chen et al., Adv. Funct. Mater 21 (24), pp. 4617, 2011]. However, theses surfaces offer low interfacial area for heat transfer. In order to achieve high heat transfer rates, high interfacial area between the substrate and the drop is required [Miljkovic et al., ACS Nano 6(1), pp. 1776, 2012]. Nonetheless, high interfacial area increases the drop Contact Angle Hysteresis (CAH) which hinders drop self-detachment and DWC heat transfer. Therefore, there is a dilemma between high drop interfacial area in contact with the substrate (drop in Wenzel state or Partial Wetting (PW)) and low CAH.

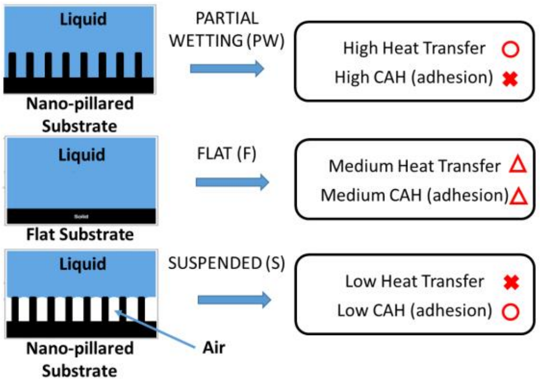

Figure 1 – Sketch of interfacial contact between drop and substrate; Partial Wetting, Flat and Suspended. Properties: △ Current, O Desired and X no desired

２．研究の目的

The physical binary interactions between liquids and solid surfaces that combine micro- and nano-features are not fully understood yet. During condensation phase-change the surface structure and its intrinsic wettability is found to play a crucial role during the dynamics of condensation and on the heat transfer performance. Hence, in this work I investigated the wetting behavior of water on flat and on micro-textured surfaces with different nano-scale roughness and wettability orientation at the microscale (Environmental Scanning Electron Microscope (ESEM)) and at the macroscale. Fundamental physics unveiled here will be applied for the design of low adhesion surfaces (low Contact Angle Hysteresis (CAH)), with high drop-surface interfacial area (wetting) for enhanced heat transfer.

The main objectives of this research are;
(A) the control drop migration on flat surfaces by wettability gradients at the microscale that can induce low CAH. I will exploit the migration phenomenon at the macroscale proposed by Chaudhury and Whitesides, Science 256, 1992, and I will extend this work to the microscale. Induce drop migration from PW regime by the combination of micro-textured surfaces with wettability gradients. This latter takes advantage of the high heat transfer rates of PW and the low CAH of S for enhanced drop self-departure. The migration from the side of the pillar to its top on a single micropillar was shortly published after the recipient of this grant in in Orejon et al. RSC Advances 6, 2016 (see section 4 of this report).
(B) Study of surface structure from the micro- to the nano-scale and wettability underneath condensing droplets.
(C) Development of high efficient DWC surfaces by scaling the knowledge unveiled at the microscale to the macroscale. This surfaces aim for the efficient droplet self-detachment due to low CAH. Thus the optimum configuration of micro- and nano-features and wettability will be elucidated.

３．研究の方法

Surfaces:
Micropillared surfaces were provided by Professor Sushanta Mitra listed as research collaborator 5. Different micropillar aspect ratio and micropillar spacing varying in wettability: hydrophilic, hydrophobic and patterned wettability, *i.e.*, hydrophilic tops and hydrophobic bottom and side of the pillars, were fabricated.
Superhydrophobic micro- and nano-structured surfaces varying in the density and the size of the microstructures were fabricated at Shanghai Jiao Tong University under the supervision of Professor Peng Zhang (research collaborator 7). The different size and density of the microstructures was controlled by the different temperature and the time of the etching

solution. In addition, solely nanostructured superhydrophobic surfaces were also fabricated.
Soft-lithography replicated *Galdiolus dalenii* bioinspired samples were fabricated at the Indian Institute of Technology Mandi research collaborator 8.

Experimental Observations:
Experimental observations at the microscale were carried out in an Environmental Scanning Electron Microscope (ESEM) FIB-ESEM Versa 3D (FEI Company, Hillsboro, Oregon, USA) at the Mechanical Engineering Department at Kyushu University. More details about the procedure on the experimental observations can be found in the Supplementary Information in Orejon et al. RSC Advances 6, 2016 (journal article 6). On the other hand, experimental observations in the presence of non-condensable gases at the macro- and the micro-scale were carried out in an insulated environmental chamber PK-3KT (ESPERC Corp.) where ambient temperature and relative humidity can be finely controlled. A Keyence zoom lens VH-Z500R was used for the experimental observations at the microscale in the presence of non-condensable gases. Other experimental observations were carried out in a custom-built optical microscope with coaxial LED illumination from Sigma Koki Co., Ltd (Japan). A RICOH lens was used for macroscopic observations.
Cooling bath, Peltier stage, steam generator, clean booth, was also acquired and used for experimental observations.

Software:
Matlab® and ImageJ software were used for image processing and analysis.

４．研究成果
(1) The effective patterned wettability gradient between the hydrophobic sides of the micropillar and the hydrophilic top was confirmed. The very first droplet migration on a non-flat patterned wettability surface was published shortly after the recipient this proposal.

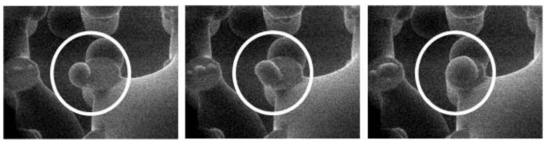

Fig. 2 – Droplet migration from the side to the top of the micropillar. Micropillar diameter and height is 50 micrometers.

Based on our experimental observations, we found that smaller droplets need greater fraction of the triple phase contact line on the hydrophilic top for the migration to occur. This is due to the greater hysteresis opposing to the droplet migration in the case of small droplets, since the size/scale of such droplets is in a similar order of magnitude to those of the nanostructures decorating the micropillars' sides, which was reported in in Orejon et al. RSC Advances 6, 2016. Aiming to ease the droplet migration from the micropillar side to its top, we designed a new batch of micropillars with the same diameter but 25 microns in height. On this latter batch, the migration of the condensate was not observed, presumably due to the different arrangement (horizontal versus vertical) of the nanostructures present at the micropillars' sides.

(2) To further understand the effect of surface structure underneath the condensate, we undertook experimental observations on hydrophilic micropillared surfaces. Aiming for the control of the condensation behavior, we designed three different micropillared configurations based on thermodynamic principles. The surfaces proposed had the same aspect ratio, *i.e.* same height/diameter, and different spacing between the structures. As a consequence, a Simultaneous Dropwise and Filmwise Condensation behavior in a completely hydrophilic structured surface is reported here for the very first time:

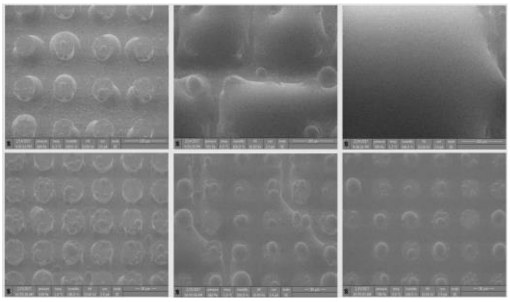

Fig. 3 – (top) Filmwise condensation and (bottom) Simultaneous Dropwise/Filmwise condensation for short structure spacing.

In addition, a heat transfer resistance based analysis is proposed to estimate the different heat transfer performance when comparing the simultaneous occurrence of dropwise and filmwise condensation to solely filmwise condensation. The optimum design for maximizing the heat transfer on such surfaces is then proposed, which is included in Orejon et al., International Journal of Heat and Mass Transfer 114, 187-197, 2017.

(3) The effect of surface structure underneath condensing droplets on micro- and/or nano-structured superhydrophobic surfaces is addressed here. Typically, upon coalescence of two of more droplets on a superhydrophobic surface, new coalesced droplets are able to jump out of the surface offering refreshed area for droplet re-nucleation and growth, which is characteristic of high heat transfer. We here studied the condensation performance of three superhydrophobic surfaces varying in the size and density of the microstructures. The coalescence-induced droplet-jumping performance is evaluated:

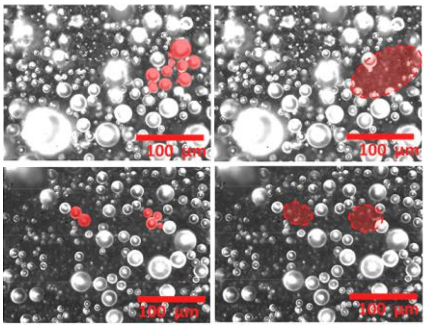

Fig. 4 - Characteristic coalescence-induced droplet-jumping performance on (top) micro-/nano- and (bottom) nano-structured superhydrophobic surfaces. From Zhang et al. ACS Applied Materials and Interfaces 9 (40), 35391-35403, 2017.

Although, the presence of microstructures increases effectively the area for heat transfer, and hence it should provide greater heat transfer performance, we on the other hand report that microstructures do actually suppress the droplet-jumping performance of micrometer droplets. The suppression of the self-removal of micrometer droplets has hence a negative impact on the heat transfer performance. We report that the main mechanisms for the suppression of the droplet-jumping performance is the angular deviation from the main surface normal introduced by the microstructures. Droplets growing at the sides of the microstructures do not contribute fully to the release in kinetic energy in the out-of-plane direction and hence the jump does not occur.

(4) Bioinspired functional surfaces are receiving great attention due to their excellent self-adapted self-cleaning, anti-fogging and fog harvesting performance. In this work we evaluate the surface replication via soft-lithography of the biological sample of the *Gladiolus Dalenii*. Fixated and replicated samples were subjected to Environmental Scanning Electron Microscopy (ESEM) and to optical microscopy in the absence and presence of non-condensable gases, respectively to demonstrate the effective replication on the mechanisms of nucleation and growth on fixated and replicated samples.

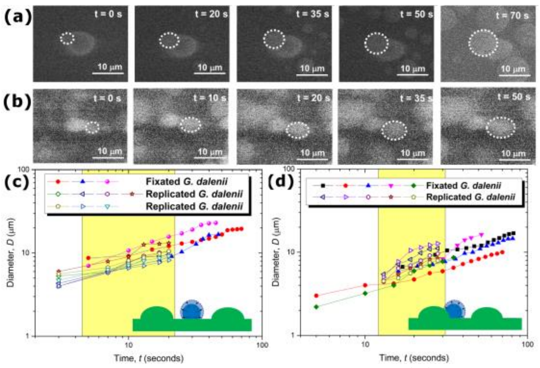

Fig. 5 - Characteristic ESEM on (a) fixated and (b) replicated *G. Dalenii* samples. The replication of the droplet growth on both fixated and replicated as droplet diameter, *D*, vs. time is demonstrated. From Vipul et al. ACS Sustainable Chemistry and Engineering 6 (5), 6981-6993, 2018.

Besides demonstrating the effective replication of surface structure and the mechanisms of droplet nucleation and growth on both fixated and replicated *G. Dalenii* leaves, the fog harvesting performance was investigated.

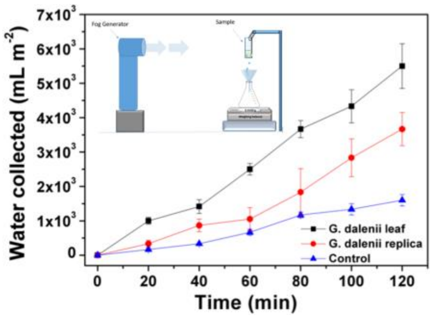

Fig. 6 - Amount of water collected versus time on fixated and replicated *G. Dalenii* leaves and control sample. From Vipul et al. ACS Sustainable Chemistry and Engineering 6 (5), 6981-6993, 2018.

The greater fog harvesting performance on the fixated *G. Dalenii* leaf when compared to the replicated one and to the control sample is reported, which is attributed to the more hydrophobic nature of the fixated biological sample when compared to the replicated one.

Nonetheless, to highlight is the up to 200% greater fog collection performance in the case of the replicated *G. Dalenii* sample when compared to the control one. For the same intrinsic wettability, the replicated sample is able to yield twice as much water collected. The greater fog harvesting performance in the case of the replicated leaf is solely due to the introduction of the unique arrangement of the micro- and nano-structures present in the natural sample when compared to the smooth flat control one.

５．主な発表論文等

（研究代表者、研究分担者及び連携研究者には下線）

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〔図書〕（計　0　件）

〔産業財産権〕

○出願状況（計　0　件）

名称：
発明者：
権利者：
種類：
番号：
出願年月日：
国内外の別：

○取得状況（計　0　件）

名称：
発明者：
権利者：
種類：
番号：
取得年月日：
国内外の別：

〔その他〕
ホームページ等

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