ISSN: 0976-3376

Available Online at http://www.journalajst.com

ASIAN JOURNAL OF
SCIENCE AND TECHNOLOGY

Asian Journal of Science and Technology
Vol. 14, Issue, 05, pp. 12513-12516, May, 2023

RESEARCH ARTICLE

EXTREME WETTABILITY CONTRAST IN HYBRID SURFACES FOR ENHANCING DEW COLLECTION

***TB Nguyen and Vinh NT**

Thai Nguyen University of Education, Thai Nguyen, Vietnam

ARTICLE INFO

Article History:
Received 13th March, 2023
Received in revised form
02nd April, 2023
Accepted 20th May, 2023
Published online 30th May, 2023

Keywords:
Water collection, Wettability,
High contrast, Hybrid.

ABSTRACT

This study proposes the investigation of water harvesting on the hybrid surface with different super hydrophilic sizes, which is inspired by the water-capturing behavior of the Stenocara beetle. The combination of water collection (superhydrophilic spots) and water-driven (superhydrophobic area) facilitates the water collection process on such a unique morphology. The results describe the importance of contact angle hysteresis in the determination of collection efficiency. The higher hysteresis difference leads to the larger critical droplet volume and can be explained through the wettability contrast at the boundary. The critical volume calculation of a single droplet has been carried out and demonstrated a good correlation with the condensation mass. This result figures out the appropriate hydrophobic-hydrophilic combination and proposes a model for water collection on a hybrid surface.

Citation: ***TB Nguyen and Vinh NT.* 2023.** "Extreme wettability contrast in hybrid surfaces for enhancing dew collection", *Asian Journal of Science and Technology*, 14, (05), 12513-12516.

INTRODUCTION

Dew collection refers to the harvesting of water droplets suspended in the air. In the Namib Desert, dew is an alternative water source for the life[1]. Darkling Beetles utilize their own body with elytra surfaces on the dorsal as a dew collector assuming characteristic fog-basking [2]. Thomas Norgaard *et al.* have reported O.unguicularis as the only one of investigated beetles that assumes the head standing fog-basking behavior, while the Stenocaragracilipes presented the highest water collection efficiency [1]. Inspired by this interesting behavior, the dew collection has attracted much attention from researchers of the potential to become a water source[3]. Water condensation is a sequential process consisting of 3 steps; nucleation, condensation, and coalescence[4]. First, the nucleation appears and attracts the neighbor vapor. The condensed small droplets become large droplets via coalescence together. Finally, the water droplet falls by the gravity force[5]. During the water condensation process, the wettability and morphology of the surface give influence each step. Therefore, controlling the wettability and morphology of surfaces in water condensation are the most important factors because it is a key phenomenon in water harvesting, heat exchange systems, and even energy conversion [6,7]. Numerous research works focused on water condensation topics have been introduced[7,8,17–20,9–16]. Many types of surfaces with different techniques have been carried on to improve water-capturing behavior[7,8,13,16,19]. Among various approaches that have been reported, the hybrid pattern inspired by Namib Desert beetles can be considered a potential structure for water harvesting, guiding to large applications in water collection devices, especially in hot and unstable weather regions[8,9,18,21]. In recent years, hybrid surfaces which contained hydrophilic/superhydrophilic regions based on the hydrophobic/superhydrophobic background have been considered a new key phenomenon for water harvesting and outperform the collection performance compared with other functional surfaces[8,9,18]. This high performance is attributed to the hybrid surface's unique structure, which consisted of different wettabilities contrast. Owing to the low energy barrier for nucleation, water droplets are easily found in high wettability states such as hydrophilic and superhydrophilic[22]. These tiny droplets rapidly coalesce with the neighboring droplets and maximize their volume before falling when gravity overcomes the capillary force. The water repellent property of hydrophobic/ superhydrophobic has proposed an important role in condensed droplets' "falling ability" [9,13,18,20]. Water droplets with really high contact angle hysteresis will be stuck in the hydrophilic area, inheriting the thermal transformation for extending the volume, therefore falling harder and expressing a much lower volume compared to the other surfaces. The advantages of hybrid pattern surfaces in water harvesting also have been observed especially for a long-time condensation experiment and broad temperature range [12,17]. However, the reported researches still possess the contrast between investigated results and even with artificial samples as well. The reason might be attributed to the lack of theoretical calculation for a well-designed hybrid surface. This work aims to evaluate the water condensation efficiency of high wettability contrast hybrid samples with different hydrophilic dots. The unit cell was maintained at 600um to mimic the Stenocara beetle back's morphology while the hydrophilic spot was verified from 300 to 500um. The single formation of critical droplets will be observed to figure out the effects of participating factors such as advancing contact angle, and droplet size. Obtained results also will be compared with a theoretical approach to document the optimized combination for enhancing dew collection in hybrid surfaces. The superhydrophobic, superhydrophilic, and bare Aluminum will be used as references to demonstrate the advantage of a hybrid surface for water collection from moisture.

Experimental setup

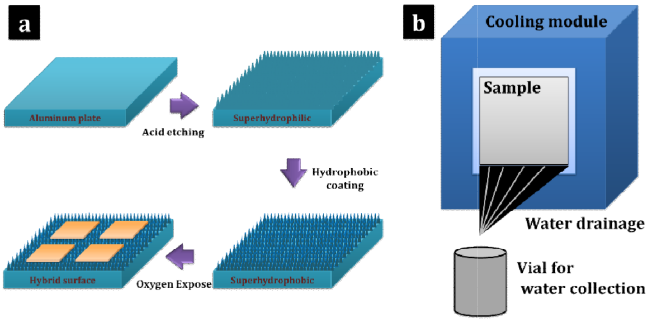

Figure 1. The fabrication process (a) and experimental setup for dew collection (b)

Figure 1 describes the hybrid surface manufacturing process. The bare Al surface first was cleaned in order with Acetone, Iso-Propanol, and Ethanol to remove all dust and residual oxides on the surface. By using sandpaper to initially grind the surface, followed by etching using Hydrochloric acid, the hydrophobic disappeared and the surface became superhydrophilicwith a water contact angle of around 10°. The modification process was followed by sonication with DI water several times to remove all acid and aluminum powder residues. For making the superhydrophobic-based area, the etched surface was coated with PFPE (PerfluoroPolyEther) solvent for 1 hour and followed by drying for 1 more hour in the ambient air. After chemical coating, the surface resulted in a super-hydrophobic surface with a very high water contact angle (>160°) and extremely low sliding angle (<2°).

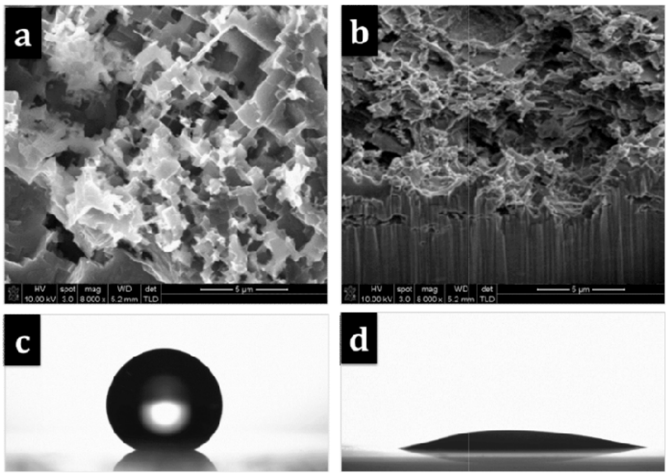

Figure 2. SEM (a) and FIB images (b) of etched Al surface, corresponed contact angle on superhydrophobic (c) and superhydrophilic (d)

To investigate the correlation between superhydrophilic and superhydrophobic parts on the hybrid surface, we have used shadow masks in the treatment process. Superhydrophobic surfaces were attached to the masks of different sizes (300um, 400u, and 500um) and followed by UVO exposure during the process. The covered area remained in a superhydrophobic state while exposed spots exhibited a completely wetting state with a water contact angle below 10°. The completely superhydrophilic surface and bare Al were cleaned and rinsed in DI water for reference. The investigation of dew collection has been carried out inside the environmental chamber maintained at the standard condition (27°C in temperature and 60% in humidity) for 4 hours and repeated at least 5 times before collecting the average. The hybrid surfaces were compared with the uniform surfaces including the original Al plate, superhydrophobic and superhydrophobic surfaces.

RESULTS AND DISCUSSIONS

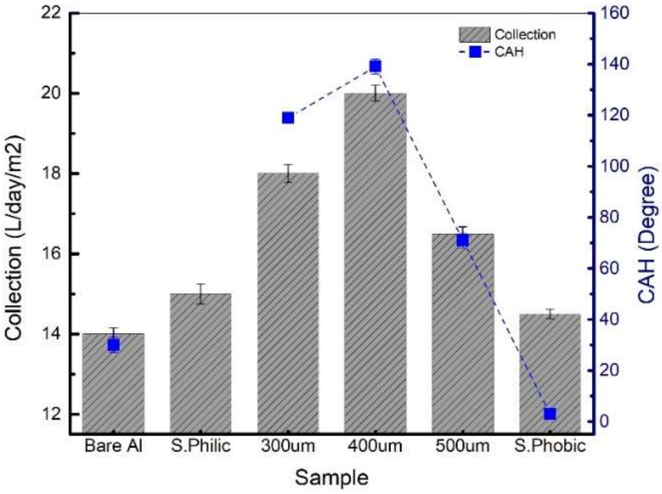

Figure 3. Water collection on different morphologies

Table 1. Measured values for examined surfaces

No.	Hydrophilic	Hydrophobic	θ	θ_r	θ_a	V_{crit} (mm^3)
1	300	600	145	42	160	3.7
2	400	600	142	20	159	5.5
3	500	600	138	19	90	3.47
4	Completely hydrophilic		15	--	--	
5	Completely hydrophobic		162	165	2	
6	Bare		82	115	67	

In contrast to the superhydrophobic and hydrophilic (Bare) samples, drop-wise condensation was obtained on superhydrophobic and hybrid surfaces. This is due to the chemical coating when the water droplets are found difficult to contact with surface roughness, resulting in a single droplet on the surface. A little difference was observed in the bare surface case when water droplets condensed on the different regions spontaneously to create water "bumps", but rapidly coalescence and formed a water film on the surface. On the other hand, the water collection on hybrid samples exhibited preeminence compared to the single wettability samples. All hybrid samples illustrated the high water collection ability with at least 16.7 (L/m^2/day), about 11,3% higher than superhydrophilic and 19.3% higher than superhydrophobic surfaces.

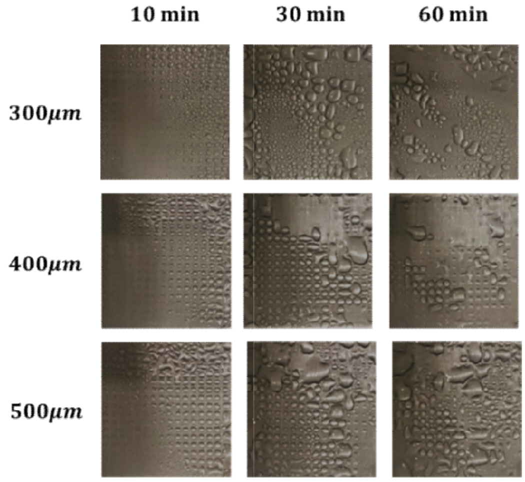

Figure 4. Condensation process on surfaces with different morphologies and wettabilities

Especially, the results showed that surfaces with 400um of spot size expressed the highest performance in water condensation followed by 300um in size while the 500um sample presented low ability in the collection. It can be explained by the correlation between the volume of droplets and the distance between hydrophilic spots. The condensation depends on both the nucleation and coalescence process, so the volume of a water droplet on hydrophilic size should be considered together with the distance between neighbor hydrophilic parts. The critical droplets of three surface morphologies will be calculated based on the measure factor (Table 1) using the calculation model which was first introduced by Furmidge for predicting the condensation efficiency[23]. The critical volume can be expressed as followed:

$$V = \frac{\pi(1-\cos\theta_a)^2(2+\cos\theta_a)}{2\sin^3\theta_a} w^3$$

In which $V,\theta,$ w is critical volume, advancing contact angle, and diameter of a single droplet, respectively. Table 1 indicates the calculation of critical volume based on the advancing and receding angle. Interestingly, the highest volume was found at 400um and the smallest one belonged to 500um. The calculated values were plotted against the corresponding droplet diameter and critical volume based on equation 1. The higher the advancing contact angle and droplet size we can generate, the higher the critical volume we can achieve. The higher receding contact angle results in the low spreading tendency of the water droplet, therefore preventing heat transfer for the consecutive nucleation process. Hence, the optional combination should be considered by observing the contact angle hysteresis parameter when it was the result of combined effects from surface morphology and wettability.

CONCLUSIONS

In this work, we present the investigation of water harvesting on the hybrid surface of different sizes which was inspired by the Stenocara beetle's wing structure. The combination of water collection from the hydrophilic spots and water-driven from the hydrophobic surrounding area facilitated the water collection process on such a unique surface. The results described the dramatic advantage of 400 – 600 in the unit cell compared to the other sizes, illustrating the good correlation with nature-inspired morphology. The difference in contact angle hysteresis leads to the larger critical water droplet and can be explained through the unique contrast between hydrophobic and hydrophilic areas. Further investigation figured out the correlation between hydrophilic size and contact angle hysteresis and proposed a mechanism for water collection on a hybrid surface. The consecutive investigation will focus on the other topographies of the hybrid forms such as circle, oval, or parallel sections.

Acknowledgment: This work was supported by the Thai Nguyen University of Education – Thai Nguyen University, Vietnam. The authors would like to express our sincere appreciation.

REFERENCES

T. Nørgaard, M. Dacke, Fog-basking behaviour and water collection efficiency in Namib Desert Darkling beetles, Front Zool. 7 (2010) 23. https://doi.org/10.1186/1742-9994-7-23.

A.R. Parker, C.R. Lawrence, Water capture by a desert beetle, Nature. 414 (2001) 33–34. https://doi.org/10.1038/35102108.

C.R. Tracy, N. Laurence, K.A. Christian, Condensation onto the Skin as a Means for Water Gain by Tree Frogs in Tropical Australia., Am Nat. 178 (2011) 553–558. https://doi.org/10.1086/661908.

A.F. Mills, R.A. Seban, The condensation coefficient of water, Int J Heat Mass Transf. 10 (1967) 1815–1827. https://doi.org/https://doi.org/10.1016/0017-9310(67)90052-X.

I. Snustad, I.T. Røe, A. Brunsvold, Å. Ervik, J. He, Z. Zhang, A review on wetting and water condensation - Perspectives for CO2 condensation, Adv Colloid Interface Sci. 256 (2018) 291–304. https://doi.org/https://doi.org/10.1016/j.cis.2018.03.008.

A. Lee, M.-W. Moon, H. Lim, W.-D. Kim, H.-Y. Kim, Water harvest via dewing, Langmuir. 28 (2012) 10183–10191. https://doi.org/10.1021/la3013987.

S. Danilo, C. Dominique, P. Frédéric, Experimental dropwise condensation of unsaturated humid air – Influence of humidity level on latent and convective heat transfer for fully developed turbulent flow, Int J Heat Mass Transf. 102 (2016) 846–855. https://doi.org/https://doi.org/10.1016/j.ijheatmasstransfer.2016.06.001.

H. Li, Z. You, H. Zhang, Experimental investigation on the heat transfer enhancement of steam condensation on tube with hydrophilic-hydrophobic hybrid surface, J Phys Conf Ser. 2280 (2022) 12059. https://doi.org/10.1088/1742-6596/2280/1/012059.

K.-S. Yang, K.-H. Lin, C.-W. Tu, Y.-Z. He, C.-C. Wang, Experimental investigation of moist air condensation on hydrophilic, hydrophobic, superhydrophilic, and hybrid hydrophobic-hydrophilic surfaces, Int J Heat Mass Transf. 115 (2017) 1032–1041. https://doi.org/https://doi.org/10.1016/j.ijheatmasstransfer.2017.08.112.

P.S. Mahapatra, A. Ghosh, R. Ganguly, C.M. Megaridis, Key design and operating parameters for enhancing dropwise condensation through wettability patterning, Int J Heat Mass Transf. 92 (2016) 877–883. https://doi.org/https://doi.org/10.1016/j.ijheatmasstransfer.2015.08.106.

Z. Deng, C. Zhang, C. Shen, J. Cao, Y. Chen, Self-propelled dropwise condensation on a gradient surface, Int J Heat Mass Transf. 114 (2017) 419–429. https://doi.org/https://doi.org/10.1016/j.ijheatmasstransfer.2017.06.065.

S. Chung, K. Kadala, H. Taylor, Stable dropwise condensation observed on a hierarchically structured superhydrophobic surface incorporating micro-domes, Microelectron Eng. 225 (2020) 111252. https://doi.org/https://doi.org/10.1016/j.mee.2020.111252.

R.A. Pinheiro, A.A. Silva, V.J. Trava-Airoldi, E.J. Corat, Water vapor condensation and collection by super-hydrophilic and super-hydrophobic VACNTs, Diam Relat Mater. 87 (2018) 43–49. https://doi.org/https://doi.org/10.1016/j.diamond.2018.05.009.

A. Chatterjee, M.M. Derby, Y. Peles, M.K. Jensen, Condensation heat transfer on patterned surfaces, Int J Heat Mass Transf. 66 (2013) 889–897. https://doi.org/https://doi.org/10.1016/j.ijheatmasstransfer.2013.07.077.

A. Starostin, V. Valtsifer, Z. Barkay, I. Legchenkova, V. Danchuk, E. Bormashenko, Drop-wise and film-wise water condensation processes occurring on metallic micro-scaled surfaces, Appl Surf Sci. 444 (2018) 604–609. https://doi.org/https://doi.org/10.1016/j.apsusc.2018.03.065.

S. Baba, K. Sawada, K. Tanaka, A. Okamoto, Dropwise Condensation on a Hierarchical Nanopillar Structured Surface, Langmuir. 36 (2020) 10033–10042. https://doi.org/10.1021/acs.langmuir.0c00950.

B. Qi, J. Wei, X. Li, Enhancement of condensation heat transfer on grooved surfaces: Numerical analysis and experimental study, Appl Therm Eng. 115 (2017) 1287–1297. https://doi.org/https://doi.org/10.1016/j.applthermaleng.2016.10.207.

C.-W. Yao, J.L. Alvarado, C.P. Marsh, B.G. Jones, M.K. Collins, Wetting behavior on hybrid surfaces with hydrophobic and hydrophilic properties, Appl Surf Sci. 290 (2014) 59–65. https://doi.org/https://doi.org/10.1016/j.apsusc.2013.10.188.

E.K. Her, T.-J. Ko, K.-R. Lee, K.H. Oh, M.-W. Moon, Bioinspired steel surfaces with extreme wettability contrast, Nanoscale. 4 (2012) 2900–2905. https://doi.org/10.1039/C2NR11934J.

M.M. Garimella, S. Koppu, S.S. Kadlaskar, V. Pillutla, Abhijeet, W. Choi, Difference in growth and coalescing patterns of droplets on bi-philic surfaces with varying spatial distribution, J Colloid Interface Sci. 505 (2017) 1065–1073. https://doi.org/https://doi.org/10.1016/j.jcis.2017.06.099.

Z. Chen, Z. Zhang, Recent progress in beetle-inspired superhydrophilic-superhydrophobic micropatterned water-collection materials, Water Sci Technol. 82 (2020) 207–226. https://doi.org/10.2166/wst.2020.238.

R.P. Sear, Nucleation: theory and applications to protein solutions and colloidal suspensions, *J Phys Condens Matter.* 19 (2007) 033101. https://doi.org/10.1088/0953-8984/19/3/033101.

C.G.L. Furmidge, Studies at phase interfaces. I. The sliding of liquid drops on solid surfaces and a theory for spray retention, J Colloid Sci. 17 (1962) 309–324. https://doi.org/https://doi.org/10.1016/0095-8522(62)90011-9.

****