Proceedings of the 12th International Conference on Fluid Flow, Heat and Mass Transfer (FFHMT 2025)
July 15, 2025 - July 17, 2025 | Imperial College London Conference, London, United Kingdom
Paper No. 129
DOI: 10.11159/ffhmt25.129

A Hybrid Surface Design for Superior Condensation Heat Transfer

Xu Chen[1], Tsz Chung Ho[1], Chi Yan Tso[1, *]
[1]School of Energy and Environment, City University of Hong Kong, Hong Kong, China
xche23-c@my.cityu.edu.hk; tc.ho@cityu.edu.hk; *chiytso@cityu.edu.hk

Extended Abstract

Condensation heat transfer on metallic heat transfer surfaces is crucial to diverse thermal engineering applications. However, inefficient removal of high-thermal-resistance condensed droplets from metallic heat transfer surfaces leads to elevated thermal resistance, significantly reducing condensation heat transfer efficiency [1]. To tackle this challenge, researchers have developed various surface modification strategies, with micro-grooved structures and biphilic surface modification being two of the most promising approaches. Regarding micro-grooved structures, this technique involves the creation of durable microscale grooves on metallic heat transfer surfaces, which effectively increase the condensation area beyond the planar surface. These structures induce anisotropic condensation patterns and facilitate directional transport of condensate droplets, thereby improving condensation heat transfer. However, the inherently high surface energy of micro-grooved structures causes strong liquid-surface adhesion, promoting undesirable filmwise condensation and ultimately compromising heat transfer performance [2]. In contrast, biphilic surface modification entails the fabrication of spatially distributed hydrophilic sites on superhydrophobic substrates with low surface energy. These hydrophilic sites act as preferential nucleation centers, guiding droplet formation and enhancing droplet transport through mechanisms such as coalescence-induced jumping and sliding. Despite these advantages, the durability of biphilic surfaces is limited due to prolonged droplet residence time, which accelerates structural degradation [3]. Micro-grooved structures enhance effective condensation area and regulate droplet removal but are limited by excessive droplet adhesion. Meanwhile, biphilic surfaces improve nucleation-coalescence dynamics but suffer from poor durability. Herein, we propose an integrated surface modification strategy for metallic heat transfer surfaces that synergistically combines these two approaches to overcome their inherent limitations, achieving superior droplet mobility and enhanced condensation performance. To integrate the advantages of both approaches, we developed the micro-grooved biphilic surface. This surface combines the strengths of micro-grooved structures and biphilic surface modifications to overcome their respective limitations. Hydrophilic sites with an optimized 0.9% area ratio were coated onto the micro-grooved surface to regulate nucleation and enhance droplet mobility through coalescence-induced jumping and sliding [4]. Additionally, the effect of groove depth on condensation performance was investigated, and an optimal depth was identified to maximize droplet removal while minimizing liquid retention. Specifically, we observed that as the micro-groove depth increased, the condensation performance exhibited a trend of first increasing and then decreasing. The optimal condensation performance was achieved at a micro-groove depth of 0.15 mm, where droplet mobility and heat transfer efficiency were maximized. The micro-grooved biphilic surface achieves superior condensation performance by balancing droplet mobility, nucleation control, and surface adhesion, effectively addressing the limitations of existing techniques. This advancement holds significant potential for improving energy efficiency in thermal management systems and fostering the development of sustainable technologies in industrial and environmental applications.

References

[1] S. Chen, R. Wang, F. Wu, H. Zhang, X. Gao, and L. Jiang, “Copper-based high-efficiency condensation heat transfer interface consisting of superhydrophobic hierarchical microgroove and nanocone structure,” Materials Today Physics, vol. 19, p. 100407, Jul. 2021.

[2] B. Qi, J. Zhou, J. Wei, and X. Li, “Study on the wettability and condensation heat transfer of sine-shaped micro-grooved surfaces,” Experimental Thermal and Fluid Science, vol. 90, pp. 28–36, Jan. 2018.

[3] Y. Zhu, C. Y. Tso, T. C. Ho, M. K. H. Leung, S. Yao, and H. H. Qiu, “Heat transfer enhancement on tube surfaces with biphilic nanomorphology,” Applied Thermal Engineering, vol. 180, p. 115778, Nov. 2020.

[4] Y. Zhu, T. C. Ho, H. H. Lee, M. K. H. Leung, and C. Y. Tso, “Droplet jumping physics on biphilic surfaces with different nanostructures and surface orientations under various air pressure conditions,” Cell Reports Physical Science, vol. 3, no. 4, p. 100849, Apr. 2022.