materials proceedings

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Proceeding Paper

Fabrication and Characterization of Paraffin-Based Slippery Liquid-Infused Porous Surfaces for Applications of Condensation Heat Transfer †

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† Presented at the 6th Conference on Emerging Materials and Processes (CEMP 2023), Islamabad, Pakistan, 22–23 November 2023.

Abstract: Phase change materials, such as paraffin waxes, have recently been introduced in surface science. Paraffin-based slippery liquid-infused porous surfaces (P-SLIPSs) provide switchable wettability and various adhesion states. Herein, P-SLIPSs were fabricated on copper plates. To study condensation heat transfer, two condensation rigs were fabricated and optimized via a comparison between the experimental and theoretical heat transfer coefficients, finding a good agreement in the short cold-finger-assisted rig. The condensation mode on P-SLIPSs is dropwise mode. Consequently, the condensation heat transfer coefficients on P-SLIPSs were found to be higher compared with that of pristine copper plates.

Keywords: slippery surfaces; condensation heat transfer; paraffin waxes

Citation: Gulfam, R.; Cheema, I.I.; Ishrat, Y.; Askari, M.A.; Lv, F. Fabrication and Characterization of Paraffin-Based Slippery Liquid-Infused Porous Surfaces for Applications of Condensation Heat Transfer. *Mater. Proc.* **2024**, *17*, 7. https://doi.org/10.3390/materproc2024017007

Academic Editors: Sofia Javed, Waheed Miran, Erum Pervaiz and Iftikhar Ahmad

Published: 9 April 2024

1. Introduction

Condensation has become a widespread subject of research across the globe, categorized into two fundamental modes: filmwise and dropwise. It has been frequently reported that dropwise condensation provides a ~4–5 times higher heat transfer coefficient than that of filmwise condensation [1]. With the aim of enhancing the heat transfer efficiency of condensation systems via dropwise mode, the introduction of slipperiness onto condensing surfaces has led to more conducive results [2]. For the realization of slipperiness, various kinds of oils and lubricants have been employed in recent years. Majorly, the slippery liquids are of two types: phase invariant materials (e.g., silicon oil) and phase change materials (e.g., paraffin wax) [3]. In order to hold those oils onto and into the metallic condensing surfaces, surface chemistry alteration is quite cumbersome and requires in-depth expertise in surface science and surface energies. The usual method to alter the surface chemistry is to introduce hydrophilicity–hydrophobicity via chemically driven oxidation-etching approaches, thereby generating a series of nano-confinements that suck and hold the oils. Such surfaces are typically termed slippery liquid-infused porous surfaces (SLIPSs).

In this paper, thin copper plates were oxidized and infused with paraffin wax. Surface characteristics and condensation dynamics were studied, finding the enhanced heat transfer coefficients on P-SLIPSs.

2. Materials and Methods

Copper plates (20 mm × 20 mm × 0.4 mm, purity 99.99%) were bought from local vendors in China. Paraffin wax with a melting temperature of 60–62 °C was bought from Sinopharm Chemical Reagent, China. The oxidized layer on the copper plate was created via the process of a high-temperature alkaline solution (aqueous solution of sodium hydroxide and ammonium persulfate). The oxidized layer was coated with the superhydrophobic material at ambient temperature for 1 h. The superhydrophobic-coated oxidized layer was then heat treated at 120 °C for better cross-linking of the superhydrophobic material. Then, paraffin wax was infused via a dip-coating process performed at a temperature of 80 °C.

The long cold-finger-assisted condensation rig was fabricated via a steel chamber consisting of a pressure transducer, a chiller, and a vacuum pump. The short cold-finger-assisted condensation rig was fabricated via a styrofoam chamber.

3. Results and Discussions

3.1. Criterion to Fabricate the Condensation Rigs

Although the condensation rig simply consists of a steam generator, a chiller connected with a cold finger, and a few auxiliary instrumentation facilities, adequate design of the prototype is highly essential to avoid the mismatch between the experimental and theoretical heat transfer coefficients. We attempted to fabricate two condensation rigs with the conclusion that there should be an optimum length of a cold finger through which condensation heat can be efficiently transferred. The first rig is the long cold-finger-assisted (LCF) rig, as shown in Figure 1a,b, while the second is the short cold-finger-assisted (SCF) rig, as depicted in Figure 1c,d. It should be noted that all condensation experiments were conducted at 1 atm.

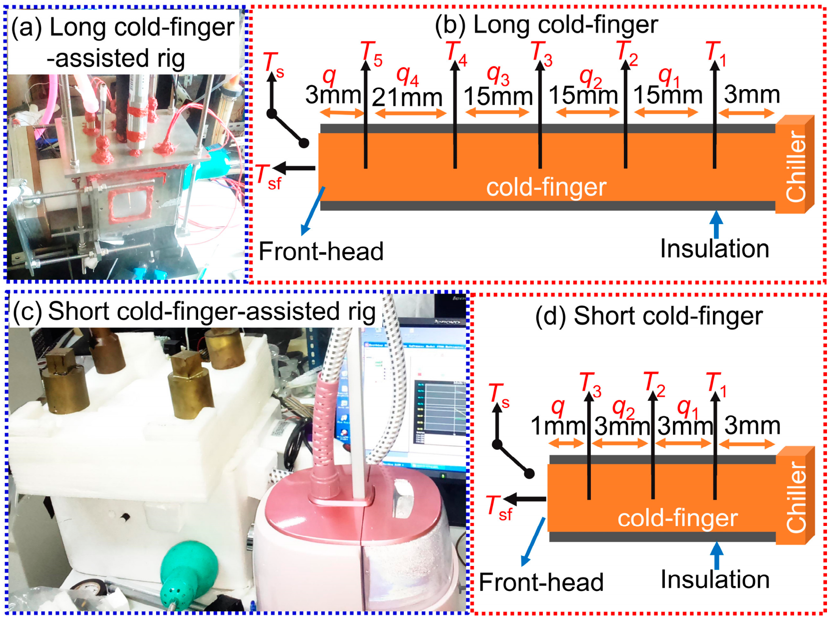

Figure 1. Condensation setups: (**a**,**b**) long cold-finger-assisted rig; (**c**,**d**) short cold-finger-assisted rig.

The cold finger in LCF is 72 mm long, along which five T-type thermocouples T_5 (near the front head), T_4, T_3, T_2, and T_1 (near the chiller) are inserted at axial distances of 3 mm, 24 mm, 39 mm, 54 mm, 69 mm, and 72 mm, respectively. There are two immersion heaters, each with a power of 150 W. The head of the cold finger acts as a pristine copper surface when P-SLIPSs are not attached to it.

The cold finger in SCF is 10 mm long, with three T-type thermocouples (T_1, T_2, and T_3) with an inter-distance of 3 mm, while T_3 is, in particular, 1 mm away from the front head. There is one plate-type immersion heater, which has a power of 1800 W.

The condensation heat flux q was calculated via linear extrapolation with respect to the local temperatures (T_1 to T_5) as follows:

$$q_1 = -k\frac{T_1 - T_2}{\Delta x_{1\sim 2}} \ldots\ldots\ldots (a),\ \ q_2 = -k\frac{T_2 - T_3}{\Delta x_{2\sim 3}} \ldots\ldots\ldots (b),\ \ q_3 = -k\frac{T_3 - T_4}{\Delta x_{3\sim 4}} \ldots\ldots\ldots (c),$$
$$q_4 = -k\frac{T_4 - T_5}{\Delta x_{4\sim 5}} \ldots\ldots\ldots (d),\ \ q_5 = -k\frac{T_5 - T_{sf}}{\Delta x_{5\sim head}} \ldots\ldots\ldots (e) \quad (1)$$

where k refers to the thermal conductivity of the pristine copper plate (400 $Wm^{-1}K^{-1}$). The heat flux q_5 (kWm^{-2}) can be taken as the mean of q_1, q_2, q_3, and q_4, providing the value of q as shown in Equation (2):

$$q_5 = \frac{q_1 + q_2 + q_3 + q_4}{4} = q \quad (2)$$

With the known value of q and T_5, T_{sf} (surface temperature) is calculated by rearranging Equation (1) as follows in Equation (3):

$$T_{sf} = \frac{q \times \Delta x_{5\sim head}}{k} + T_5 \quad (3)$$

q is the heat flux of conduction that should be equal to the heat flux of convection during the condensation process. Hence, q serves as the heat flux in the Newton's law of cooling, as depicted in Equation (4):

$$h = \frac{q}{T_{sub}},\ T_{sub} = T_s - T_{sf} \quad (4)$$

T_{sub} is the difference between the steam temperature T_s and the condensing surface temperature T_{sf}, which is overall called the sub-cooling temperature, varying inversely with heat transfer coefficient h. Nusselt's model of filmwise heat transfer coefficient h_t (also known as theoretical heat transfer coefficient) is given as follows in Equation (5):

$$h_t = 0.943 \times \left[\frac{h_v \rho^2 g k^3}{(T_s - T_w)\mu L}\right]^{1/4} \quad (5)$$

where h_v is the latent heat of vaporization, ρ is the density of water, k is the thermal conductivity of water, μ the is viscosity of water, L is the length of the condensing surface, and g is the gravitational force under which condensation from the vertical wall takes place.

The criterion for the accurate working of condensation rigs is to maintain the equivalence between h and h_t. The results obtained from the LCF unit are shown in Figure 2a. By adopting a similar heat flux calculation method, the results obtained from the SCF unit are depicted in Figure 2b, establishing a good match between h and h_t.

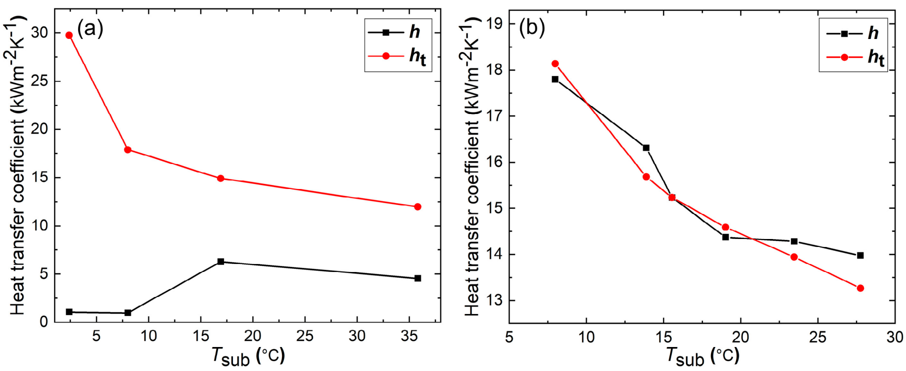

Figure 2. Comparison of theoretical and experimental heat transfer coefficients for (**a**) long cold-finger-assisted (LCF) and (**b**) short cold-finger-assisted (SCF).

3.2. Condensation Patterns and Heat Transfer Coefficients

Based on the optimum results as discussed above, the SCF rig was employed to study the condensation dynamics of pristine copper plates and P-SLIPSs. Condensation patterns of pristine copper plates are depicted in Figure 3a–c, while those for P-SLIPSs are demonstrated in Figure 3d–l. Via the developed mathematical modeling and linear extrapolations of heat flux, the heat transfer coefficients (*h*) were calculated and are represented in Figure 3m. It is inferred that *h* is prone to being adversely affected due to poor water droplet removal and the intrinsic hydrophilic behavior of the pristine copper surface. Conversely, modifying the surface chemistry leads to an easy removal rate on behalf of slipperiness that accelerates the speed of departure, thus immediately rendering the surface ready for re-nucleation. This whole mechanism can be deeply understood in Figure 3d–l, which encompasses water droplet nucleation (first appearance), shedding-off, and eventually re-nucleation on P-SLIPSs within seconds. Moreover, it can be observed that as long as the water droplet appears, most of them prefer to coalesce and then slide off the surface under the effect of gravity and with ease owing to the oiliness of the paraffin wax surface. With the departure of droplets, some sites appear to be the paths along which droplets move straightforwardly until they leave P-SLIPSs.

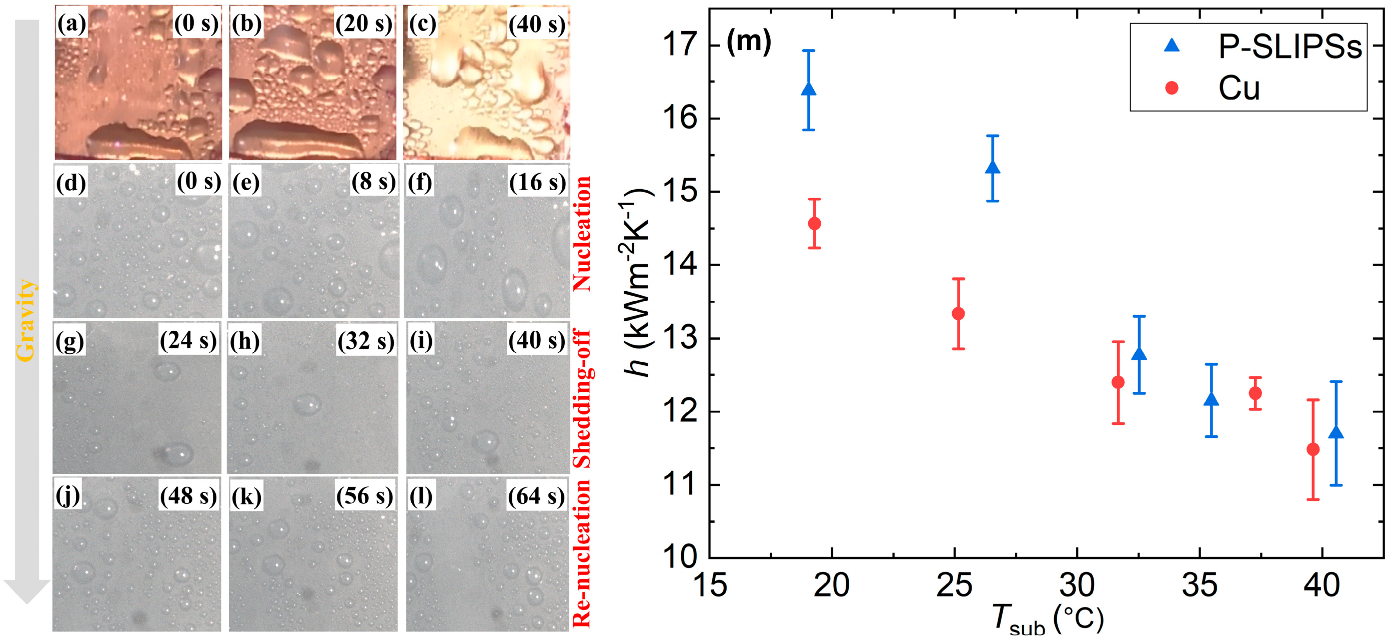

Figure 3. (**a**–**c**) Filmwise condensation on copper plate; (**d**–**l**) dropwise condensation on P-SLIPSs in liquid phases; and (**m**) heat transfer coefficients.

The efficient working performance of as-prepared P-SLIPSs can be analyzed via a graphical representation of the heat transfer coefficient shown in Figure 3m. It is evident that *h* is higher in the case of P-SLIPSs than copper (Cu), for which the main reason is ascribed to the efficient heat transfer due to less interfacial adhesion between droplets and oily surfaces.

Author Contributions: Conceptualization, methodology, validation, writing—original draft preparation, writing—review and editing, supervision, project administration, funding acquisition, R.G.; writing—original draft preparation, writing—review and editing, I.I.C.; writing—original draft preparation, writing—review and editing, Y.I.; writing—original draft preparation, writing—review and editing, M.A.A.; writing—original draft preparation, writing—review and editing, F.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by National Science Foundation of China under the Research Fund for International Scientists (Grant No. 5221101369) and from the China Postdoctoral Science Foundation under the 72nd Batch of General Funding (Grant No. 2022M720711) and the APC was funded by both.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data can be obtained by sending a reasonable request to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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