Condensation Heat Transfer Performance of Nano-Engineered Cu Surfaces

Hyunsik Kim and Youngsuk Nam*
Department of Mechanical Engineering, Kyung Hee University, 1732 Yongin, 446-701, Korea

*E-mail: ysnam1@khu.ac.kr

Abstract. We investigated condensate mobility and resulting heat transfer performance on Cu based water repellent surfaces including hydrophobic, superhydrophobic and oil-infused surfaces. We observed the transient microscale condensation behaviours up to 3 hours with controlling the supersaturation level at 1.64. We experimentally characterized the nucleation density, droplet size distribution and growth rate, and then incorporated them into the developed condensation heat transfer model to compare the condensation heat transfer performance of each surface. Due to the spontaneous coalescence induced jumping, superhydrophobic surface can maintain the high heat transfer performance while other surfaces show a gradual decrease in heat transfer performance due to the increase in the thermal resistance across the growing droplets. We also quantified each thermal resistance values from the vapor to the surface through the droplets to find out the relative importance of each thermal resistance term.

1. Introduction
Condensation behavior has been studied actively for decades to improve heat and mass transfer performance. Condensation heat transfer performance can improve the efficiencies in water harvesting, thermal management facilities, power plants, as well as in desalination and air conditioning.

Copper is a useful material in many industrial applications due to its high thermal conductivity, easy manufacturing, and relatively low price. In many systems such as power plants, copper has been applied to efficiently reject the heat to the surrounding via condensation.

To enhance condensation heat transfer performance, condensed droplets must be rapidly removed from the surface to minimize the thermal barrier. Recently, researchers showed that super-hydrophobic surfaces provides a higher mobility of condensates, which may enhance the heat transfer performance[1-3].

Here, we investigated the condensate mobility and resulting heat transfer performance on nano-engineered Cu surfaces. We introduced scalable Cu nano surfaces with unique wetting characteristics and observed the transient microscale condensation behaviors using a high-speed microscopy and a temperature and humidity controlled stage. Unlike previous heat transfer model studies based on the nucleation density correlations[2,4], we experimentally characterized the nucleation density, droplet size distribution and growth rate, and then incorporated them directly into the developed condensation heat transfer model to compare the condensation heat transfer performance of each Cu nano condenser surface more precisely.
2. Experimental method

2.1. Surface fabrication
We fabricate hydrophobic copper (HPo), super-hydrophobic copper oxide (SHPo), and oil infused super-hydrophobic copper oxide (Oil+SHPo) surfaces to observe the condensation phenomena on each surface. The CuO nanostructured copper surfaces are formed with a chemical oxidation process using hot alkali solution\[^1\], and modified by TFTS (Sigma Aldrich) vapor deposition process. The Oil+SHPo is fabricated by infusing Krytox oil (DuPont) on the SHPo surface.

Figure 1 shows the field emission scanning electron microscopy (FE-SEM) images of CuO nanostructures which have uniform height approximately 1 μm. Table 1 shows contact angles (CA) on each surface, and we can predict the droplet mobility via the contact angle hysteresis. The HPo surface has almost 30° CA hysteresis, so the condensed droplets cannot be removed easily. The SHPo and Oil+SHPo surfaces have the CA hysteresis less than 5 degrees, so the droplets have high mobility.

![FE-SEM image of nano-engineered copper oxide surfaces.](image)

Table 1. Contact angle on each surface.

|               | Advancing($\theta_a$) | Receding($\theta_r$) | Static($\theta_s$) |
|---------------|-----------------------|----------------------|-------------------|
| HPo           | 122.6°±2.8            | 81.9°±8.8            | 118.7°±2.4        |
| SHPo          | 165.1°±1.6            | 159.8°±3.3           | 161.2°±1.6        |
| Oil+SHPo      | 120.1°±1.1            | 118.7°±1.5           | 119.3°±0.6        |

2.2. Condensation experiment
Figure 2 shows the experimental set-up for observing condensed droplet growth. Nitrogen gas is supplied the chamber through the DI water. Then measured temperature and humidity were 18.34±1.23 °C and 70.85±4.12%. The sample is cooled down to 5.93±0.11 °C by cold plate which is cooled by thermal bath. Droplets were condensed on the horizontal surface, and were observed via an optical microscope (BX51M, Olympus) and we take the images of droplets on three to five points of each surfaces.

![Schematic image of the condensation experiment setup.](image)

To quantify the condensate rate, we used a super-saturation level ($s$)\[^5\], then we can compare the condensation performance at the same conditions by making $s=1.64$.

3. Results and discussion

3.1. Droplet growth rate and surface coverage
Figure 3 (a) shows the condensed droplets on each surface up to 3 hours. Droplets on HPo continuously grow on their initial position due to high CA hysteresis, however droplets on Oil+SHPo
are merged actively with the neighbor droplets because they can move easily by low CA hysteresis. On both surfaces, most area are covered by droplets after ~180 min although some small droplets are present between the large droplets, because when the large droplets return to circular shape after two or more droplets merged, then the condensate nucleation start on the appeared refreshed area. The SHPo shows different behavior with other surfaces. Even after condensation time passed, the size are almost same compared with the initial stage due to the droplet jumping phenomena\(^3\) i.e., the phenomena that droplets jump away from the surface without extra energy due to the released surface energy during the coalescence. Then the size of the droplets on SHPo seems to be near constant due to the repeated droplet disappearance and regeneration.

By measuring the observed images, we obtained the average individual droplet diameter \((2R)\) and sum of droplet-surface contact area \(π(R\sinθ)^2\) as a function of condensation time (Figure 3 (b) and (c)). The Oil+SHPo has high growth rate, then the average droplet size is higher than HPo at the initial ~30 min. Because the droplets on the Oil+SHPo have high droplet mobility by low CA hysteresis, then the droplets are merged easily. While the droplets on HPo grow up alone, on Oil+SHPo are become bigger by droplet merging phenomena. After 30 min, however, growth rate on Oil+SHPo decrease because no more merging happened, then the droplets on HPo become bigger after 120 min.

Surface coverage shows almost same tendency on both surfaces, although the growth rate was different. While the Oil+SHPo has large droplets by merging the HPo has high droplet density. Therefore surface coverage on HPo becomes similar with Oil+SHPo. The rate of surface coverage decreases on both surfaces after 30 min, because uncovered bare area is exposed by returning circular shape after merging.

The SHPo maintains a small droplets size and low contact area even after long time. The average diameter and surface coverage are maintained near constant, under 15 μm and 0.05 due to the active droplet jumping behaviors.

![Figure 3.](image)

3.2. Heat transfer performance

The condensation heat transfer performance is calculated using the thermal network model for HPo, SHPo and Oil+SHPo (as in Figure 4 (a), (b) and (c)) including various thermal resistances at liquid vapor interface, inside droplet, structures and coatings. The HPo only has a surface coating while the SHPo has nanostructures and partially impregnated water above the Cu₂O layer which is formed when the process of change copper to copper oxide.
Using the droplet growth rate and the nucleation densities obtained from the microscopic experiments, we calculate the heat transfer rate through each individual droplet, measured via experiment.

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q_{SHPo} = \frac{\pi R^2 \left( \frac{\Delta T - \frac{2T_{sat}\sigma}{R h_{fg} \rho_w}}{h_{fg}(1 - \cos \theta) + \frac{R \theta}{4 k_w \sin \theta}} + \frac{1}{k_{hc} \sin^2 \theta} \left[ \frac{k_{CuO} \theta}{\delta_{CuO} k_{CuO} + h k_{hc}} + \frac{k_a (1 - \varphi)}{\delta_{h} k_w + h k_{hc}} \right]^{-1} \right) + \frac{\delta_{CuO}}{\sin^2 \theta k_{CuO}}} \]

Eq. (1)

Here, \( R \) is droplet radius and \( \sigma \) is water surface tension. \( h_{fg} \) and \( h_i \) are the latent heat of vaporization and condensation interfacial heat transfer coefficient. \( k_w, k_{hc}, k_a, k_{CuO} \) and \( k_{Cu2O} \) are the thermal conductivity of water, functional coating, air, nanostructures and Cu\(_2\)O layer, respectively. Finally, \( \delta \) is the thickness of each parameter.

The overall heat flux was calculated based on Eq. (1) by aggregating the heat transfer through the individual droplets and expending the surface to 1 \( m^2 \) (Figure 5). The HPo and Oil+SHPo have high heat flux during the initial ~5 min, and the HPo has higher heat flux than the Oil+SHPo because the nanostructures and infused oil work as thermal resistance. However the heat flux on both surfaces are rapidly decrease during the initial ~30 min because droplets growth, while the SHPo is maintained near constant. Therefore, SHPo performs better than Oil+SHPo and HPo from approximately 30 min and 45 min, respectively. The SHPo has higher heat flux approximately 141% and 86% than Oil+SHPo and HPo, at 180 min, respectively.

Figure 6 shows the average thermal resistance in individual droplets by stacking each thermal resistance term at a specific time. The nanostructures & liquid resistance coloured blue indicate the resistance from nanostructures and permeated water and oil for the SHPo and Oil+SHPo, respectively. Total thermal resistance on SHPo is higher than other surfaces at 5 min due to high droplet and nanostructures conduction resistance and the total resistance are near constant due to uniform droplet size. And the thermal resistance due to the nanostructures was significant during the entire condensation event due to the near constant droplet size, which implies that the reduction of the...
thermal resistance of nanostructures may be crucial to further increase the condensation heat transfer performance of SHPo. The HPo and Oil+SHPo have lower thermal resistance, but droplets are continuously grow during condensation, then the total thermal resistance become much bigger than SHPo. For the Oil+SHPo, the thermal resistance due to the nanostructures and infused oil are significant at the beginning but the relative importance decreases as the droplet size and resulting conduction resistance through droplets get bigger. For the HPo, the droplet conduction resistance is the only influence term to heat flux.

Figure 6. Thermal resistance through the individual droplet.

4. Conclusion
In this study, we made a stable surface, which has uniform nanostructures of 1 μm, by using a hot alkali solution. Then, we made three surfaces which have different characteristics including HPo, SHPo and Oil+SHPo. By 3 hours condensation experiments, droplet growth rate and surface coverage on SHPo are maintained near constant due to high condensate mobility named droplet jumping, while on other surfaces are continuously grow due to high CA hysteresis and merging phenomena. The overall heat flux calculated by using the droplet growth rate and the nucleation densities.

The HPo and Oil+SHPo had the higher total heat flux and overall heat transfer coefficient at the initial part of condensation time. However, as the droplets on HPo and Oil+SHPo grew continuously, resulting in decreased heat transfer performance. Then the heat transfer performance on the SHPo had higher heat flux approximately 141% and 86% than Oil+SHPo and HPo at 180 min., due to the SHPo maintained by droplet regeneration.

We showed the average thermal resistance through the individual droplet. Therefore, the conduction resistance through the droplet inside was significant on HPo and Oil+SHPo during the entire time. The droplet and nanostructure, however, were both significant on SHPo due to near constant droplet size. This work demonstrates scalable Cu-based nano surfaces with investigating the condense mobility and the resulting heat transfer performance on such surfaces to help develop advanced condensers.

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