Stable and enhanced jumping condensation on monolayer superhydrophobic surface with heterogeneous wettability

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1. Introduction

Cooling system utilizing the condensation heat transfer was widely used due to the higher cooling performance than single phase heat transfer (i.e air cooling). Specifically, the condensation heat transfer was used in the nuclear power plant such as passive containment cooling system (PCCS) and condenser in power conversion system [1,2]. Higher condensation heat transfer performance can enhance not only advanced thermal safety but energy conversion efficiency at nuclear power plants. To increase the heat transfer performance of condensation heat transfer, the condensate on the surface should be eliminated at a small diameter size and the droplet density should be increased for minimization of conduction thermal resistance [3]. In terms of view, the coalescence – induced jumping condensation on superhydrophobic surface showed the 30% enhanced heat transfer coefficient compared with hydrophobic surface due to the small departure diameter [4]. The heterogeneous wettability surface, furthermore, was developed for increasing the nucleation site density as well as decreasing the droplet departure diameter [5,6]. In this paper, the monolayer superhydrophobic surface with heterogeneous wettability was developed for decrease the thermal resistance effectively. This new surface named biphilic monolayer surface has two advantages in terms of performance enhancement. Firstly, the hydrophilic spot acts as nucleation site for high droplet density and the microstructure (monolayer) allowed the condensate to depinning for effective jumping respectively (fig. 1). The detail characteristics of developed surface was demonstrated at next section.
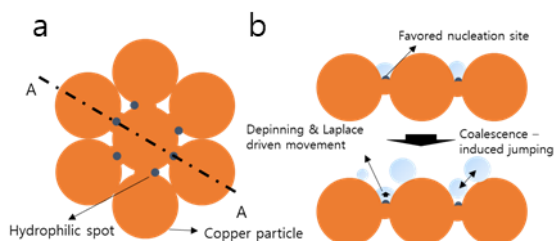

Fig. 1. The concept of the developed surface. (a) the top view of the surface. (b) the side view (A-A cross section).

2. Methods and Results

2.1 Surface fabrication

The fabrication method of biphilic monolayer surface has largely divided into the three steps. That is sintering, evaporation – crystallization, chemical oxidation and silanizing. The first step, sintering, was proceeded to make the microstructure (monolayer). The 500um copper plate was cleaned with acetone and IPA for eliminating the impurities. Then the copper particles with 25~36um size were floated on the surface by monolayer [7]. After that the sintering process in the tube furnace with 900 ℃ during the 20min, the bare monolayer surface was fabricated like fig. 2a. The second process is evaporation – crystallization [6,8]. This effective method could distribute the hydrophilic material at the specific location. Firstly, the poly (4-vinylpridine) (CAS #:25232-41-1, Sigma Aldrich) was dissolved at ethanol. Then, this solution mixed with DI water (wt % 5:2). Finally, the prepared bare monolayer surface was dipped into the mixture slowly and dried while maintaining a thin film. After repeat this process twice, the hydrophilic spot was located at gap of the copper particle. The final step for fabrication was proceeded to make the nano scale structure and hydrophobic coating layer. The alkaline solution that consisted with $NaClO_2$, $NaOH$, Na_3PO_4, $12H_2O$ and DI water (wt % 3.75:55:10:100) was used for chemical oxidation. The monolayer surface after evaporation – crystallization process was immersed in the hot alkaline solution (~95℃) during the 20min. After that, for silanizing, the silane mixture of 1ml toluene (CAS#: 108-88-3, sigma-aldrich) and 50ul trimethoxysilane (Heptadecafluoro-1,1,2,2-tetrahydrodecyl) prepared. After putting the surface and silane mixture at the jar, sealing it with wrap, the chemical deposition in the convection oven (90℃) for 3hours was started to make a hydrophobic coating layer of nm scale. From this sequence process, the biphilic monolayer surface was fabricated like fig. 2b.
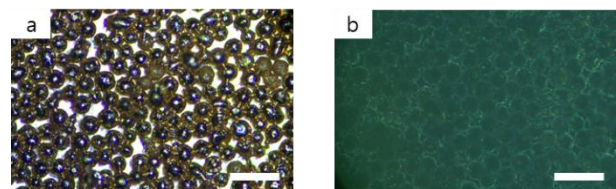

Fig. 2. The optical microscope image (a) Bare monolayer surface. (b) biphilic monolayer surface (scale: 100um)

2.2 Surface characterization

The contact angles (C.A) on the developed surface was measured using a goniometer (Smart Drop,

Femtobiomed). The measured C.A was summarized at table I. At this study, the biphilic monolayer surface was compared with superhydrophobic surface [4]. Compared with superhydrophobic surface, the biphilic monolayer surface has no difference at global wettability. However, the C.A of the poly (4-vinylpridine) film after silinizing was ~70°. If the evaporation – crystallization process proceeded succesfully, the hydrophilic material (i.e poly (4-vinylpridine)) was located at gap of particles.

Table I: C.A at each surface

	Superhydrophobic	Biphilic monolayer
Advancing C.A	172.7°±2.5°	168°±0.6°
Receding C.A	170.3°±4.6°	167.4°±0.5°
Average C.A	171.5°	167.7°

2.3 Visualization of condensation dynamics

The condensation behaviors on the biphilic monolayer surface (BM) and superhydrophobic surface (SHPo) were visualized using the optical microscope in the air-conditioned room. For the condensation visualization test, only the relative humidity was controlled. Except for the relative humidity, the other conditions (surface temperature, atmosphere temperature) were fixed 10.2℃ and 24.8℃ respectively.

At low relative humidity condition (R.H = 43%), the obvious differences were observed between two surfaces. Shown in the fig. 3, there are two distinct differences on the biphilic monolayer surface compared with superhydrophobic surface. The nucleation density was increased up to the 163% and droplet average diameter was decreased up to 37%.

From the Rose's model (eq.1) that can be predicted heat transfer coefficient of dropwise condensation, two parameters (i.e average droplet diameter, nucleation density) effected on the heat transfer coefficient dominantly [9].

$$h_{conden} = \frac{1}{\Delta T}\int_A q(r)N(r)dr \qquad (1)$$

where, the *A, ΔT, q(r), N(r)* is surface area, subcooling temperature, heat transfer rate per single droplet and droplet size distribution respectively.

In this equation, the *q(r)* increased when the droplet size was decreased due to the reduced conduction thermal resistance [9]. Furthermore, when the $\int_A N(r)dr$ is increased, the thermal resistance was decreased because it acts as parallel thermal resistance. Finally, the small

droplet diameter and large number of nucleation site can increase the heat transfer coefficient.

Contrast with the superhydrophobic surface, furthermore, the biphilic monolayer surface has favored nucleation site (i.e gap of particles) like the fig. 4. This phenomenon was similar with the previous research used the evaporation – crystallization process [6]. Due to the large wettability of the hydrophilic spot, the nucleation energy barrier was decreased compared with superhydrophobic surface [6,8,10].
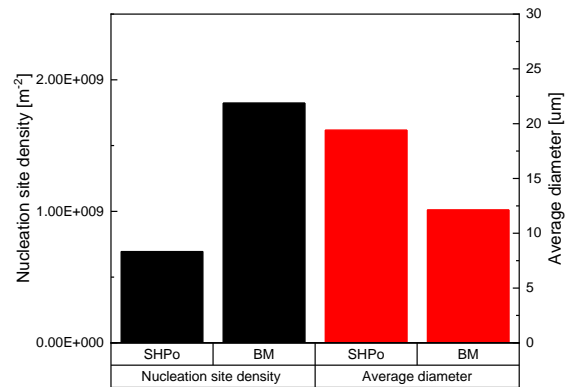

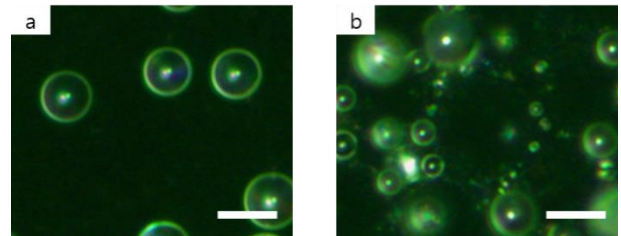Fig. 3. Result of visualization data (nucleation site density and average diameter)

Fig. 4. Comparison between superhydrophobic and biphilic monolayer about the nucleation behavior (a) superhydrophobic. (b) biphilic monolayer (scale: 15um)

Moreover, for effective coalescence – induced jumping, the adhesion energy and viscous dissipation energy interrupted the jumping should be minimized [11]. In case of biphilic monolayer surface, the bottom curvature of condensate on this hydrophilic spot was restricted due to gap of particles. So, the condensate could be depinned from the hydrophilic spot due to the laplace pressure difference between upper curvature and bottom curvature [12,13]. Depinning phenomenon also can be explained by using the depinning model [6]. Finally, the large amount of condensate could be jump from the surface effectively because of eliminated adhesion area with the surface.

At large relative humidity condition (R.H = 80%), some of the large size droplet were observed. Due to the small coalescence diameter (i.e high nucleation density), the excessive surface energy was insufficient to

overcome the adhesion energy and viscous dissipation energy at this condition [8,11]. Finally, the droplet was pinned until the falling due to the gravity force. In this case, the nucleation site density decreased due to the covered large droplet. The biphilic monolayer surface, however, the hierarchical condensation was visualized despite the large size droplet covered the surface (fig. 5). Because the large droplet on the biphilic monolayer surface was floated on the monolayer structure, the hierarchical condensation that could increase the effective heat transfer area despite the large droplet distribution was occurred [14].
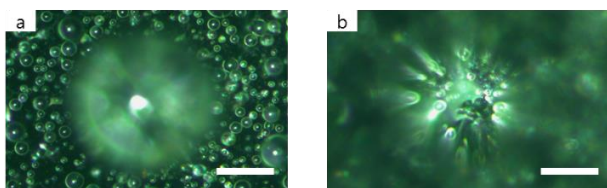

Fig. 5. Hierarchical condensation on biphilic monolayer surface (a) large droplet on the biphilic monolayer surface. (b) image focused at bottom of the same large droplet (scale: 75um)

Furthermore, if the condensates were located on the monolayer structure (fig. 5), the contact area can decrease due to the curvature of monolayer. So, the monolayer structure was effective strategy for enhanced and stable coalescence – induced jumping condensation whenever.

3. Conclusions

We developed the new jumping condensation surface using the monolayer structure and heterogeneous wettability for stable and enhanced performance. To minimize the thermal resistance caused by the condensate, high nucleation site density and small average diameter was necessary. For this, the hydrophilic spot made by the evaporation – crystallization process and monolayer that could realize the hierarchical condensation were used. The nucleation site density and average droplet diameter were increased up to the 163% and decreased 37% compared with the superhydrophobic surface respectively. From the visualization results, the enhancement rate of heat transfer coefficient can be suggested at later. Furthermore, this enhancement strategy will suggest that it can be applied to power conversion system as well as nuclear safety due to the higher condensation heat transfer performance.

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