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Enhanced dropwise condensation by oil infused nano-grass coatings on outer surface of a horizontal copper tube

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ABSTRACT

In this paper, a quick and easy method to fabricate oil infused nanograss (OIN) thin hydrophobic films for dropwise condensation enhancement is presented. Droplet sliding experiments on an inclined surface coated with this thin film infused with oil show that the droplet dripping rate can be increased considerably. Experiments of condensation heat transfer on the outer surface of a cold tube with this OIN coating show that heat transfer can be enhanced up to approximately 50% compared to raw copper surface. The enhanced condensation heat transfer by OIN coatings is due to the combination of dropwise condensation and faster removal of water droplets.

1. Introduction

Compare to film condensation, dropwise condensation is always preferred due to its significantly higher heat transfer rate. In order to guarantee effective dropwise condensation, condensate droplets must be removed quickly to prevent the formation of a liquid film [1]. In recent years, considerable interests have been given to the use of self-propelling superhydrophobic surfaces for dropwise condensation enhancement [2,3]. However, penetration of water into cavities of the superhydrophobic structures is always a critical issue, which could turn Cassie state to Wenzel state gradually and stopped superhydrophobic structures from functioning [4–7]. Although the loss of hydrophobicity could be recovered by a drying process [8], water penetration remains a roadblock for continuous dropwise condensation in long term performance. Moreover, fabrication process for superhydrophobic structures are highly depended on particular selection of substrates, and most of these processes based on lab scale recipes is expensive and difficult to be scaled up.

In this paper, we have developed a scalable manufacturing process of a soft and flexible hybrid nano coating, called oil infused nanograss (OIN). Using the saline chemistry, Polydimethylsiloxane (PDMS) chains were grafted onto various types of substrates, including but not limiting to glass, quartz, silicon, copper, stainless steel and aluminum. Silicon oil was then infused to form a deposited PDMS film, leading to a smoother surface. An OIN coating was applied on the outer surface of a copper tube (which is one of the most typical heat exchanger material) in order to study its enhancement in condensation heat transfer. It is demonstrated that steam condensing at 100 °C and 1 atm pressure outside of a horizontal copper tube with OIN coating leads to over 50% enhancement in condensation heat transfer compared to raw copper tube where cooling water inside the tube is flowing at a flow rate of 0.6 L/min at an inlet temperature of 15 to 25 °C.

2. Nanograss thin films and droplet sliding tests

2.1. Fabrication of nanograss thin films

As shown in Fig. 1, nanograss thin films were prepared by wet chemistry as follows: copper, silicon or glass was first rinsed and sonicated to obtain a clean and dust-free surface. Then, the surface of substrate was modified by vinyltrimethoxysilane. After that, polydimethylsiloxane (PDMS) chains were grafted onto the silane treated surface, and then two types of silicone oils (one with a low viscosity of 100 cSt and the other with a high viscosity of 500 mPa-s) were filled into polydimethylsiloxane (PDMS) grafted thin films.

2.2. Morphology of the oil infused nanograss coating

The thickness of the nanograss coating was measured by a scanning electron microscopy (FEI Sirion 200). A layer of 100 cSt OIN was coated on a 0.5 mm thick silicon wafer, and then taken for scanning electron microscopy. As shown in Fig. 2, the black area on the top part of SEM image was vacuum/background, and then followed by a layer of OIN shown on the middle of the image. The black area under the nanograss film was the silicon substrate. Since the nanograss film was non-electroconductive, while the silicon substrate was electroconductive, the

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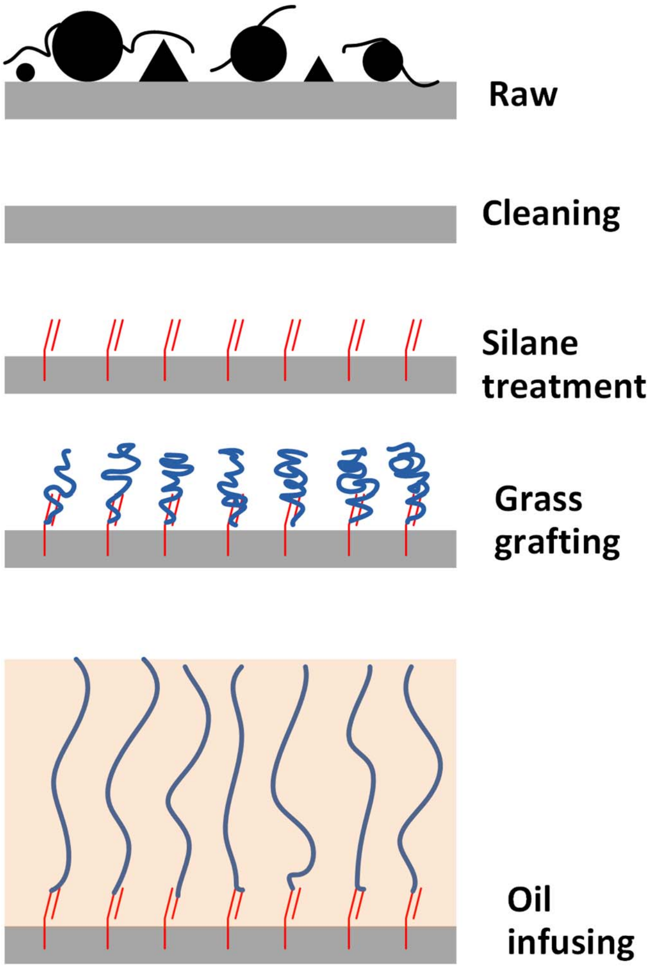

Fig. 1. Fabrication process of the nanograss coating. Length of silane molecule and polydimethylsiloxane (PDMS) molecule are not to scale.

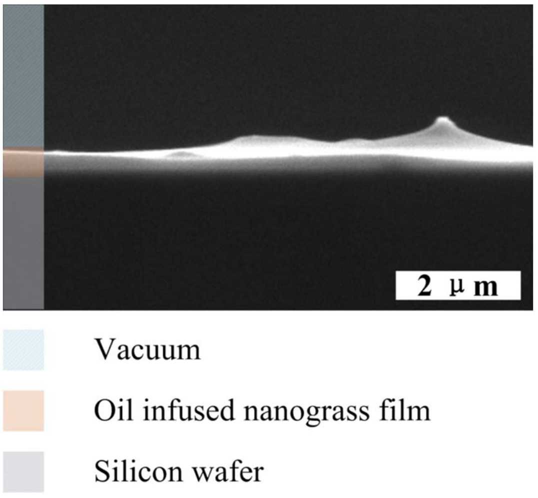

Fig. 2. SEM images of a coated nanograss film on a silicon wafer. Film was infused by silicon oil with kinematic viscosity of 100 cSt (a low viscous silicon oil).

brightness of SEM image had to be set to a relatively low value so that details of the nanograss layer could be observed. However, such particular brightness also led to the blackout of the silicon substrate. Due to the clear borderline between the blackout silicon substrate and the non-electroconductive nanograss layer, it was certain that the nanograss film had continuous coating all over the silicon wafer, and the thickness of the film could be measured from this SEM image, which was about 200 nm on the average.

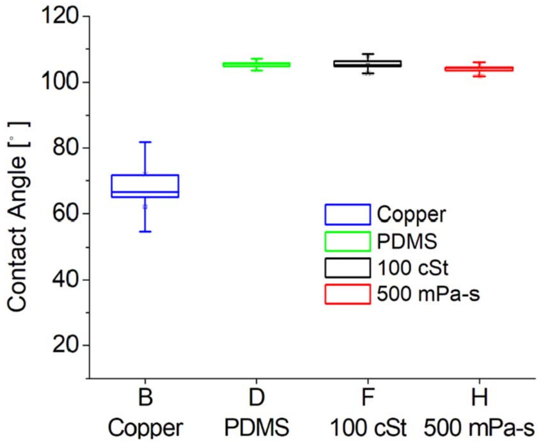

Fig. 3. Contact angle of water on copper, nanograss (PDMS) film, 100 cSt OIN film and 500 mPa-s OIN film.

2.3. *Wettability*

The amount of condensation heat flux of steam on a subcooled surface depends on the contact angle [9]. In this paper, the contact angle of the nanograss coating was measured by placing a 4 μL water droplet on top of a horizontal substrate. Fig. 3 shows that the contact angle of the droplet on a copper surface was around 68° while the contact angle of nanograss (polydimethylsiloxane (PDMS) layer) coated copper tube was about 105°, which shows that the nanograss coating could significantly increase contact angle of water on the substrate surface substantially. On the other hand, contact angles of copper tubes with 100 cSt OIN (a low viscous silicone oil) and 500 mPas (a high viscosity silicone oil) infused nanograss were around 103° and 105°, respectively. This suggested that oil infusing in the nanograss coating did not change the contact angle compared to non-oil infused nanograss coating. No matter infused with high viscous silicon oil (500 mPa-s) or low viscous silicon oil (100 cSt), the contact angle of nanograss surface remained unchanged at about 105° (see Fig. 3).

2.4. *Droplet sliding speeds*

Fig. 4(a) shows the experimental setup for droplet sliding velocity measurements. As shown, a 15 μL water droplet was placed at the top of an inclined substrate (45° with respect to the horizontal plane). Droplet sliding photos were recorded with a high-speed camera (MotionPro Y4-S3) and droplet travel distance versus time is presented in Fig. 4(b).

Fig. 4(b) shows that the droplet travel distance versus time the sliding of the water droplets depends greatly on the viscosity of the oil infused in the nanograss coating. Fig. 4(c) shows average sliding speeds on the two nanograss infused with two different oils. Although both surfaces had a contact angle of about 105°, the sliding speed of water droplet was 77 mm/s on the 100 cSt OIN film, which was 6 times faster as those on 500 mPa-s OIN film at a speed of 12 mm/s.

3. Condensation experiments

3.1. *Experimental setup and test method*

Fig. 5 shows the experimental setup for steam condensing on a copper tube with outer diameter of 6 mm and inner diameter of 4 mm, which was placed in a quartz vapor chamber. The vapor chamber was filled with water initially to a level that 5 cm below the copper tube. A heater was placed under water to generate steam that could later be