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An experimental investigation of the effect of surface roughness on sessile droplet evaporation

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ABSTRACT

As one of the most common phenomena in nature, droplet evaporation has become a major heat transfer mode and is used widely in industries and scientific fields. For a sessile droplet, the wettability of the substrate surface could make a significant effect on evaporation dynamics and heat transfer rate. Among many factors influencing surface wettability, surface roughness is one of the common causes, but the link between roughness and the processes of droplet evaporation has not yet been fully revealed. Therefore, an experimental study of sessile nanofluid water droplets located on copper surfaces with different roughness and wettability has been carried out. In the present study, the effect of roughness as a factor on the evaporation rate is considered. The deformation and temperature distribution of the liquid-vapour interface of the sessile droplet are recorded. In addition, the effect of surface roughness on the nanoparticle sedimentary pattern is observed. It has been demonstrated that the changes in surface roughness not only affect the wetting state of the sessile droplet but also have an impact on the heat and mass transfer processes at the liquid-vapour interface. The research in this article aims to recognize the relationship between roughness and droplet evaporation dynamics.

KEYWORDS: Droplet evaporation, Wetting, Surface roughness, Nanofluid, Nanoparticles sedimentation

1. INTRODUCTION

Droplet evaporation is one of the most common physical processes in nature, and the studies on sessile droplet evaporation are becoming increasingly in-depth after Maxwell first deduced the equations of droplet evaporation based on the diffusion process in the still air in 1877 [1]. Nowadays, the physical phenomenon of droplet evaporation is used widely, such as spray cooling [2], inkjet printing [3], biological and medical diagnostics [4, 5], integrated circuits manufacturing [6, 7], etc. And among the studies of sessile droplet evaporation, research on nanofluids has also attracted increasing attention [8]. Therefore, exploring the factors that could affect the sessile nanofluid droplet evaporation dynamics becomes crucial.

As a common surface property, surface roughness has been widely considered in many fields of application, such as surface preparation [9], cooling performance [10], and even medical hygiene [11]. Moreover, surface roughness also has a significant influence on droplet evaporation dynamics [12]. Therefore, it is crucial to reveal the impact of surface roughness on the nanofluid droplet evaporation dynamics and sedimentary process. Until now, surface roughness could influence the wetting phenomenon is known widely, like the state of wetting [13], contact line movement [14], evaporation mode [15], and even the Leidenfrost phenomenon [16]. Nguyen et al. [17] indicated that with the increase in surface roughness, the evaporation time is also prolonged, and many similar studies have verified this phenomenon [12]. Chen et al. [18] revealed that the surface roughness is related to the critical transition of the Cassie-Baxter state to the Wenzel state. They pointed out that the surface with

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hierarchical roughness would effectively suppress this critical transition. Gunjan et al. [19] try to integrate the dynamic roughness changes caused by air pollutants into the classical evaporation model, and the new model can predict the droplet evaporation process on the silicon surface. Siddiqui et al. [20] found that a porous structure with different porosity would form on the surface after the nanofluid droplet evaporation, and the surface roughness of residue will also increase with porosity, which will increase the evaporation rate of subsequent droplets. Up to now, the effect of surface roughness on the evaporation dynamics of sessile nanofluid droplets is still unclear. Therefore, the effects of surface roughness on the sessile nanofluids droplet evaporation remain elusive and need to be explored in depth.

As mentioned above, surface roughness could significantly influence the sessile droplet wetting and evaporation process. It also plays a vital role in the sedimentary pattern of particle-laden droplets. Batishcheva et al. [21] found that the sedimentary ring was formed on the aluminium alloy surface with the droplet loaded polystyrene particles. And a spot-like sedimentary pattern could be formed when the concentration increased. Mulka et al. [22] also explore the drying process of silica nanofluid droplets on metal substrates with different surface roughness. They found two types of crack formation logarithmic spiral and straight radially oriented. They also pointed out that the average cracking speed of straight cracks is more significant than that of spiral cracks. Meanwhile, Kim et al. [23] found that, due to the deposition of nanoparticles, the difference in the surface roughness of the sample surface decreases during the evaporation process. Liu et al. [24] also pointed out that the surface roughness of the substrate is an essential factor in affecting the sedimentation of particles. They found that the internal flow will be inhibited with the increase of surface roughness, which makes the deposition even. However, not many reports in the literature have clarified a description of the relationship between the surface roughness and the nanofluid droplet sedimentary pattern until now.

In the present research, the evaporation process of sessile nanofluid droplets on a rough copper surface was studied experimentally. Subsequently, the heat and mass transfer process of the droplet is revealed. Moreover, the effect of surface roughness on the sedimentary pattern is also investigated in this study. This study hopes to help reveal the interplay of surface roughness and nanofluidic droplet evaporation dynamics.

2. EXPERIMENTAL SETUPS AND METHODOLOGY

The environmental conditions of the laboratory are measured automatically. Relative humidity in the laboratory is 35 ± 5%. The ambient temperature and air pressure were 293 ± 3 K and 0.1 MPa, respectively. The experimental processes can be seen in Fig. 1. As shown in Fig. 1, the contact angle and droplet shape changes were measured by the Optical Tensiometer (Biolin Scientific, Finland). The thermal imaging camera (FLIR LLC, USA) also observed the liquid-vapour interface temperature distribution of the sessile nanofluid droplet, and the sedimentary pattern after the evaporation also could be recorded.

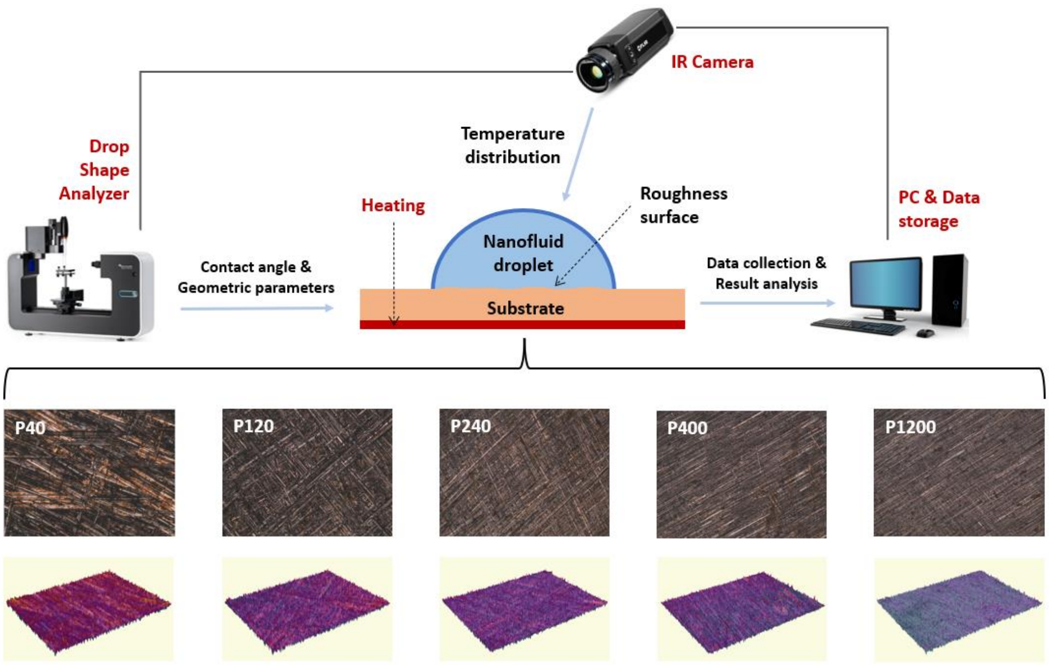

Fig. 1 Schematic diagram of experimental devices and process.

The fluids used in the experiments were deionised (DI) water and silica nanofluid, in which silica nanoparticles (SNP) were dispersed in DI water (RS PRO, UK) and followed by ultrasonication for two hours based on the two-step method. The silica nanoparticles (Sigma-Aldrich, USA) with a diameter of 0.007 μm were used in this study and were prepared at a fixed particle concentration of 0.5% volume fraction, respectively. Meanwhile, 2, 4, and 6 μL were selected as the droplet volumes used during the experiment. The sessile droplet wetting phenomenon could be described by the Wenzel model, which could be expressed as:

$$\cos\theta^* = r\cos\theta \tag{1}$$

where θ^* means the apparent contact angle, *r* means the roughness factor, and θ means Young's contact angle.

As shown in Fig. 1, the copper disc surface was polished with emery paper (3M Science, USA) through a lapping machine. The grid size of the emery papers is P40, P120, P240, P400, and P1200, respectively. The optical microscope (OPTIKA Microscopes, Italy) with cold LED light observed the surface image and the deposition appearance. Besides, the 3D colour view images were taken by the 3D optical profilometer (KLA Corporation, USA). The copper discs are fixed on the water bath heater with silicone grease (RS PRO, UK), and the surface temperature is controlled at about 40 °C.

3. RESULTS AND DISCUSSION

3.1 The effect of roughness on the surface wettability

The surface roughness would have a significant effect on the wettability. As shown in Fig. 2, when the surface roughness increases from P1200 to P40, the contact angle decreases with the increase of surface roughness. As shown in Fig. 2 (a), the contact angle of the droplet would be about 90° when located on the P1200 surface, and it will change to about 35° when located on the P40 surface. And as shown in Fig. 2 (a-c), the nanofluid sessile droplet volume would not significantly influence the contact angle. Besides, the surface roughness could significantly affect the nanofluid sessile droplet's evaporation rate. As shown in Fig. 2 (a-c), the total evaporation time of the droplet could increase about two times when the surface roughness increases from P40 to P1200.

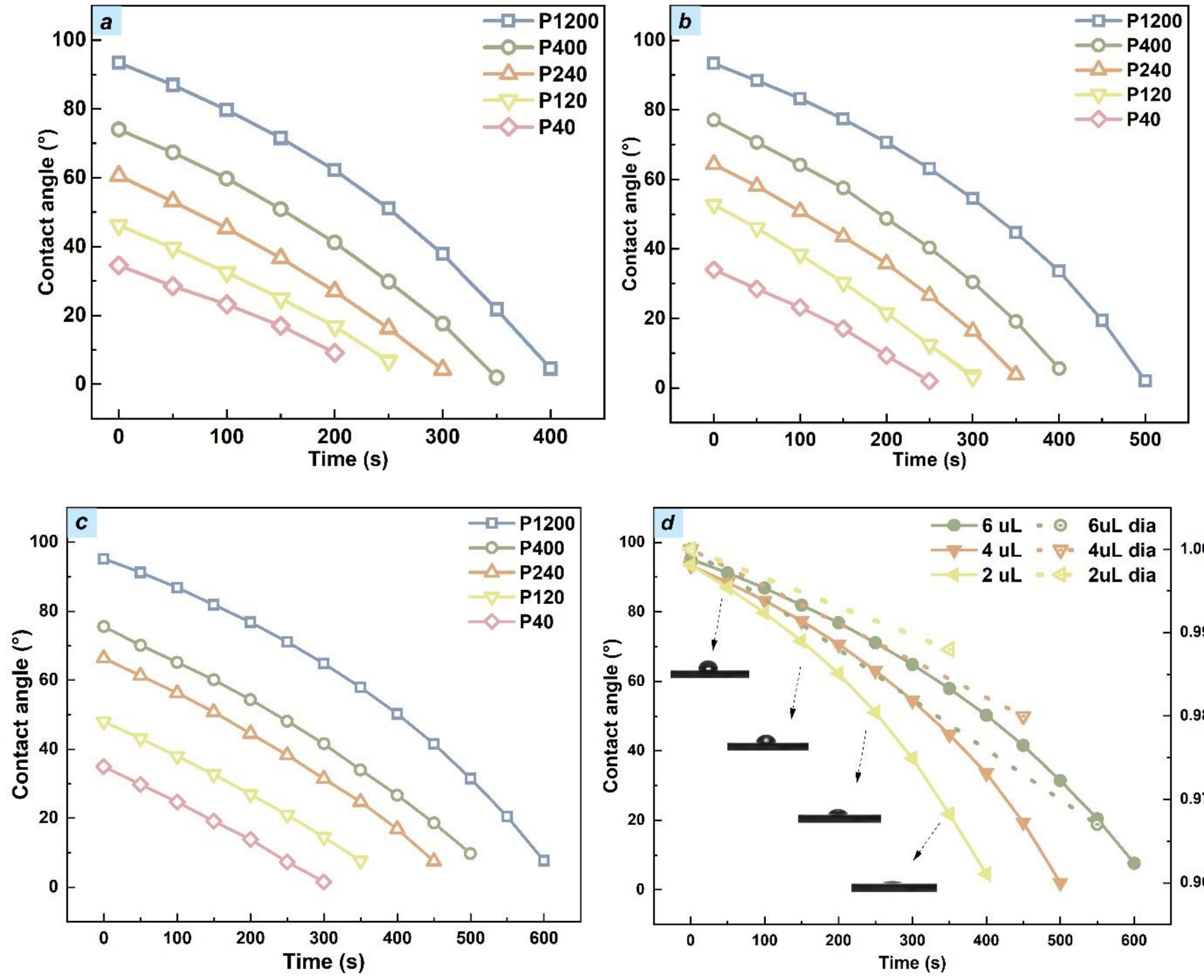

Fig. 2 The evolution of the contact angle on different rough surfaces when the sessile nanofluid droplet volume is (a) 2 μL, (b) 4 μl, (c) 6 μL; (d) The evolution of the contact angle and contact radius when a series of volume droplets located on the P1200 surface.

Then, the effect of volume on the sessile nanofluid droplet contact angle and contact radius can be seen in Fig. 2 (d). With the droplet volume increasing, the total evaporation time is also extended. And with time going, the slope of the contact angle change increases, which may be due to the heat exchange between the substrate and sessile nanofluid droplet, the solid-liquid interface, would be better and improve the evaporating rate of the liquid-vapour interface. And it also can be seen that the average evaporation rate always increases with the droplet volume on the P1200 surface, which may also owe to the bigger liquid-vapour and solid-liquid interface would improve the heat and mass transfer for the droplets. Besides, the sessile droplet contact diameter also decreases with the time on the view of the whole evaporation process, so it could be deduced that the evaporation mode is slip-slide mode (SS) in the final region.

3.2 The effect of roughness on the droplet interfacial heat transfer

The temperature distribution of the liquid-vapour interface also is studied in this study. The temperature gap refers to the temperature difference between the vertex position of the liquid-vapour interface of the sessile nanofluid droplet and the vicinity of the contact line region (the edge of the liquid-vapour interface). Then, the temperature gap for the 2 μL droplet, which is located on the surface from P40 to P1200, can be seen in Fig. 3. The temperature gap would increase with the decline of the surface roughness. It may be because the droplet contact angle and height will decrease with the roughness, and the substrate's heat is more easily conducted to the liquid-vapour interface. It would also have the effect of inhibiting the cooling effect. Therefore, the temperature gap would be smaller when the sessile nanofluid droplet is located on the rougher surface. And it also can be seen in Fig. 3 that as the evaporation proceeds, the temperature gap would be smaller, and at the end of the evaporation, the temperature gap would be very slight, even could reach to 0.1 ℃. It is also owing to the dual effects of weakened evaporative cooling effect and enhanced heat conduction effect.

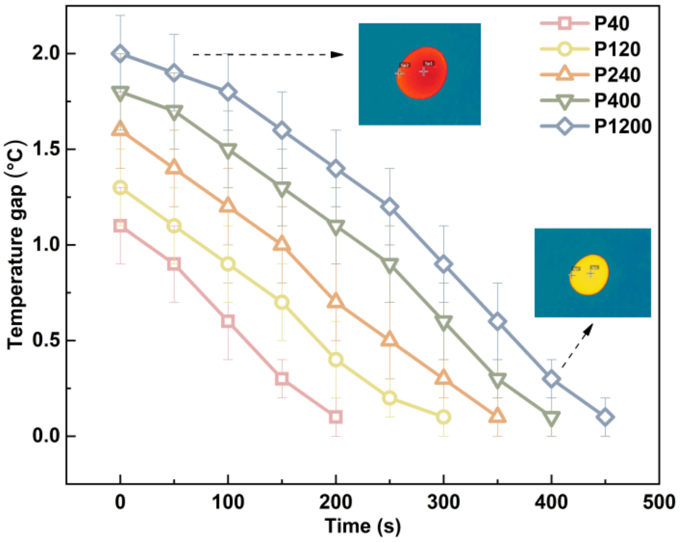

Fig. 3 The temperature gap between the top and edge of the 2 μL sessile nanofluid droplet.

3.3 The effect of roughness on the sedimentary pattern

After the evaporation, the nanoparticles would precipitate and form a sedimentary pattern, also called the coffee-ring effect [25]. The deposition patterns on different surfaces are shown in Fig. 4 (a-e), and all the sedimentary patterns correspond to the coffee ring effect. Meanwhile, the sedimentary pattern would be more evident with the decrease of the surface roughness, like it is difficult to distinguish on the P40 surface. Still, it is evident on the P1200 surface. It may be due to the uneven rough surface, so the deposits cannot be distributed evenly. At the same time, the IR images of the sedimentary pattern are listed in Fig. 4 (f-j). It can be seen from Fig. 4 (a-e) and Fig. 4 (f-j) that all the sedimentary have cracks and the cracks of the sedimentary pattern decrease with the decline of surface roughness. There are only two cracks on the surface of P1200, but the cracks are increased obviously on the P40 surface. This kind of phenomenon may be due to the more uneven height distribution of the rough surface, which makes the stress distribution of the deposited pattern of SiO_2 nanoparticles non-uniform, leading to fracture.

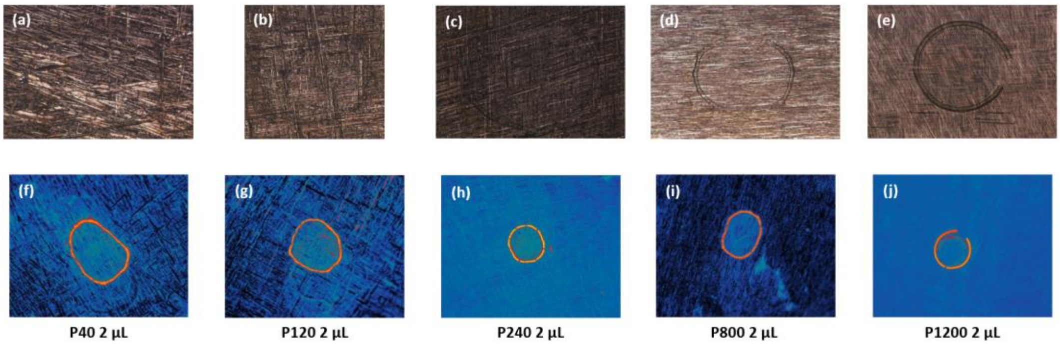

Fig. 4 The sedimentary pattern of the 2 μL sessile nanofluid droplet on the (a) P40; (b) P120; (c) P240; (d) P400; (e) P1200, and (f-j) are the corresponding IR images of the sedimentary pattern.

Besides, the sedimentary pattern's morphology distribution is also studied, which can be seen in Fig. 5 (a-c). As shown in Fig. 5 (a), the sedimentary pattern is clear, and the entire sedimentary ring is divided into two semi-rings. And the 3D topography of the blue dotted frame area is shown in Fig. 5 (b). The height of the sedimentary ring is significantly higher than other surface positions. To quantitatively analyse the height distribution of the sedimentary ring as shown in Fig. 5 (c). It can be seen that the height of the sedimentary ring is about four times taller than other surface positions.

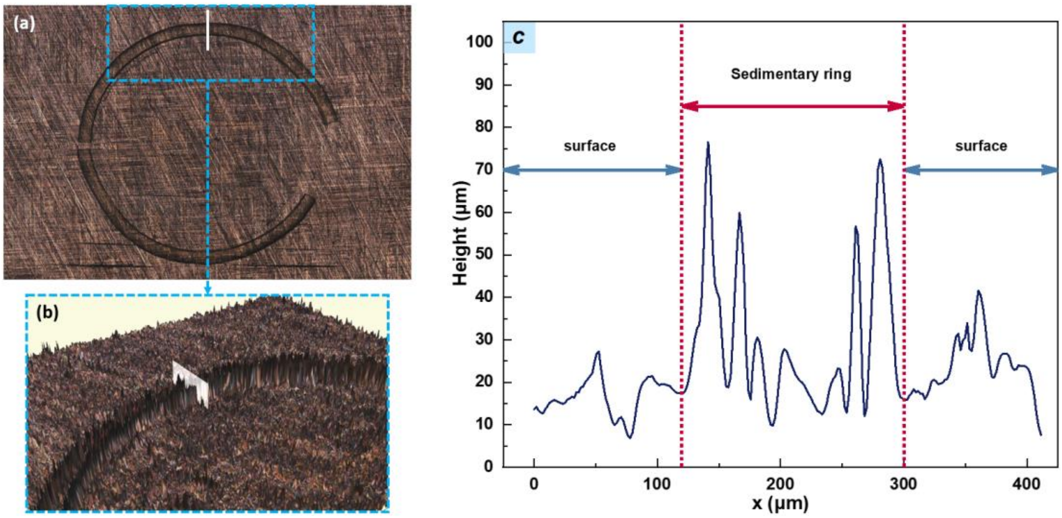

Fig. 5 (a) The image of the 2 μL sessile nanofluid droplet sedimentary pattern on the P1200 surface; (b) The 3D schematic diagram of the local position of the sedimentary ring; (c) Schematic diagram of the height distribution of the sedimentary ring section.

Meanwhile, the sedimentary ring with different volumes of the sessile nanofluid droplet can be seen in Fig. 6. As shown in Fig. 6 (a-c), all the sedimentary pattern on the P1200 surface is similar. And all deposition patterns have only 1-3 cracks, which means the smooth surface (lower surface roughness) would be conducive to forming complete coffee rings. Besides, for a more straightforward comparison, the sedimentary pattern on the P240 surface is also listed in Fig. 6 (d-f). It can be seen that the number of cracks formed on the surface of P240 increased significantly. And the sedimentary ring formed is also more irregular compared with smoother surfaces.

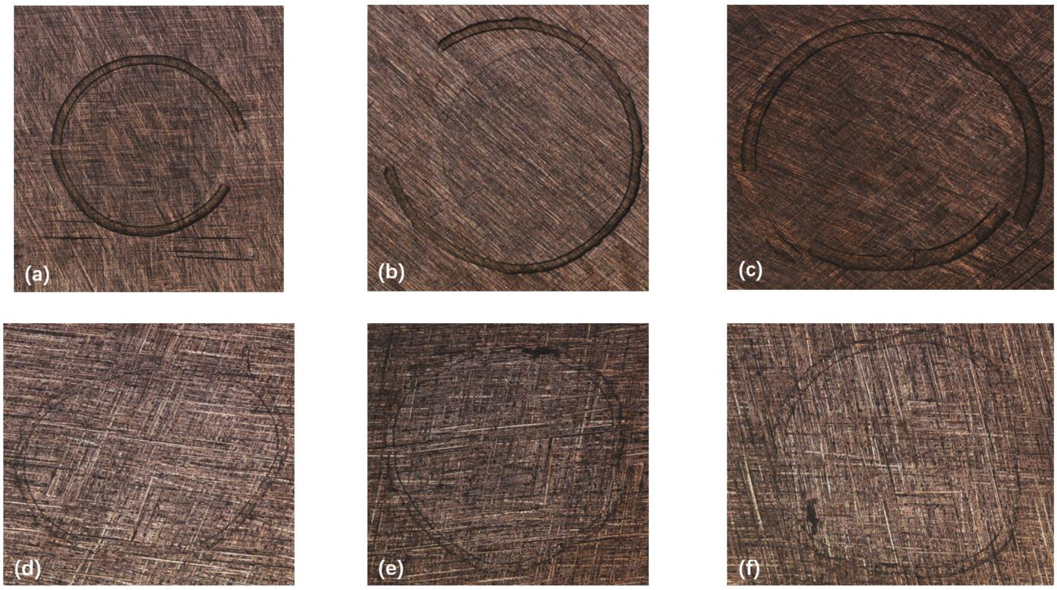

Fig. 6 The sedimentary pattern image of the (a) 2 μL, (b) 4 μL, and (c) 6 μL sessile nanofluid droplet on the P1200 surface; (d) 2 μL, (e) 4 μL, and (f) 6 μL sessile nanofluid droplet on the P240 surface.

4. CONCLUSIONS

As discussed in this study, sessile nanofluid droplet evaporation is a complex behaviour containing heat and mass transfer between the interfaces. The sedimentary process and pattern during the evaporation also need to be considered. In this study, it is demonstrated that surface roughness has a significant influence on the sessile nanofluid droplet evaporation process. The surface roughness would not only change the wettability of the copper substrate, but the evaporation rate and the contact angle change process of the droplets attached to it also be affected. Besides, the substrate surface roughness could influence the liquid-vapour interface's heat transfer process. With the roughness increase, the temperature gap between the droplet centre and edge would be smaller, and the cooling effect of the liquid-vapour interface also could be inhibited. Meanwhile, surface roughness also dramatically affects the formation of the sedimentary pattern. In this study, it has been found that the nanoparticles will form a coffee ring-like deposition pattern on surfaces with various roughnesses. However, on the smooth surface, with a lower roughness degree, the sedimentary pattern formed is more nearly complete and has fewer cracks. The research of this article hope could provide guidance and assistance in studying the sessile nanofluid droplet evaporation process.

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NOMENCLATURE

r	roughness factor		SNP	silica nanoparticles	
θ	apparent contact angle	[°]	θ^*	Young's contact angle	[°]

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