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Full Length Article

Self-propulsion of Leidenfrost droplets on micropillared hot surfaces with gradient wettability

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ABSTRACT

Motion of matter requires application of asymmetric potential. In this work, we explored the self-propulsion of Leidenfrost droplet on hot micropillared surfaces with gradient wettability. The surface fabricated with micropillars displays unidirectional properties. It was found that Leidenfrost droplets on this surface self-propelled from the smaller superficial area of micropillars (SSAM) towards the larger superficial area of micropillars (LSAM). The self-propulsion mechanism is proposed based on the self-rotation of Leidenfrost droplets and the theoretical model is well matched with the experimental findings.

1. Introduction

A Leidenfrost droplet forms when a volatile liquid is deposited on a sufficiently hot solid substrate, where the droplet suspended on the cushion of its own vapor [1–4]. This so-called Leidenfrost effect is characterized by a minimal friction and a low heat transfer coefficient between a droplet and a hot solid surface. This effect is widespread in many fields such as power generation, refrigeration, fuel injection, combustion engines [5,6] and drag reduction [7,8]. Leidenfrost droplet on Micro/Nanostructures like ratchet, array of tilted pillars can transport in a well-defined direction free from any external force [9–12]. However, when the surface temperature is above the Leidenfrost point (LFP), it becomes challenging to control and direct the motion of these high mobile droplets.

Motion of matter requires application of asymmetric potential. Some studies reported surface wettability is essential to manipulate the movement of droplets [13–15] even at high temperature. Other studies have revealed that the directional transport of droplets can be triggered by harnessing gradients of surface energy [16,17], asymmetric surface wettability [18,19] and asymmetric structural topography [20]. In addition, the liquid marbles can self-propel when placed on a water surface [21]. Furthermore, it was observed that liquid droplets can move on all kinds of surface structures with the gradient wettability at temperature below LFP or at lower temperature [22,23]. Previous studies show that the surface wettability can be modified by several methods including self-assembled monolayers [24], functional chemical species [25–27], and topographical changes [28–30]. However, surface wettability will be impaired by a long process of chemical change when a surface is heated at high temperature. Thus, it becomes significant to control the surface wettability by changing surface structures. In addition, with the development of the self-propulsion mechanism at high temperature, it is possible to design various surface structures for engineering applications, especially in high-temperature thermal systems where high energy efficiency, security and stability are of great importance.

Since Linke et al. [9] reported the self-propelled Leidenfrost droplet on ratchet surfaces, the self-propulsion of Leidenfrost droplets had become an intriguing field. Recently, Mrinal et al. [31] has reported that the self-rotation of Leidenfrost droplets can induce self-propelled motion on ratchet surfaces. However, to date there is no self-rotation of droplets observed on other surface structures.

In this study, we investigated the self-propulsion of Leidenfrost droplets on the micropillared surfaces with gradient wettability. The surface structure was fabricated by sputter coating technology and laser etching technology. It was found that the droplet deposited on micropillared surface with gradient wettability at LFP (the Leidenfrost point) self-propelled from the smaller superficial area of micropillars (SSAM) to the larger superficial area of micropillars (LSAM). The droplet motion is attributed to the escaping vapor flow beneath the droplet and a self-propulsion

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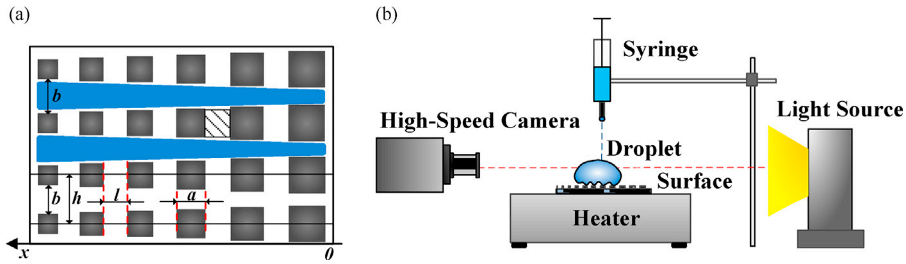

Fig. 1. Schematic of the experimental setup used to study the droplet motion on hot surfaces. (a) The top view of the surface topography. The blue area indicates the spreading area of the vapor film and the shading area is defined as a unit. (b) The sketch map of experimental setup. A liquid droplet of initial diameter D_0 = 1.13 mm falls on a heated plate and spreads to its maximum diameter D_m. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

mechanism is proposed based on the self-rotation of Leidenfrost droplets.

2. Experimental section

The experiments were carried out in the ambient temperature 21.5 °C, pressure 1 atm and relative air humidity 44%. The initial liquid temperature was equal to the ambient air temperature. Droplets were located on the horizontal micropillared surfaces. The fabrication process of surface structures is the silicon wafer was laser etched firstly and then 30 nm of copper was sputtered on the silicon surface, as a result, the micropillared surface with structural wetting gradient was fabricated. The surface structure fabricated by the physical methods can withstand high temperatures up to 500 °C. The surface features (shown in Fig. 1(a)) are square-pillar arrays with the edge length a, the height of pillars H (H = 60 μm) and the pillar-to-pillar spacing L (L = 100 μm). The initial value of the edge length a of a square pillar was 30 μm and increased at a tolerance of 4 μm until 566 μm. The gradual change of edge length of pillars result in a gradient of static contact angle from 37°to 82°(shown in Fig. 2(a)). These surfaces were used to conduct the experiment of self-propelled Leidenfrost droplets.

A schematic of the experiment setup is shown in Fig. 1. The surface was heated on the thermostatic heater and the surface temperature was measured by a thermocouple. The working fluid was deionized water. Droplets were generated by a syringe and were released close to the surface to limit the effect of the impact velocity. The volume of droplets was 6 μL (diameter of 1.13 mm). The motion of droplets was recorded by a high-speed camera (FASTEC Imaging Hispec3) with a sampling rate of 2000 frames per second. The height of the falling droplet was fixed as 5 mmThus, it was determined that the droplet impacted the surface with a velocity of 31.6 cm/s approximately. The corresponding Weber number [$We = (\rho_l d_{drop} V_0^2)/\sigma_l$] of around 2 which is considered to be relatively small (ρ_l = 998kg/m^3 and $\sigma_l = 72 \times 10^{-3}$N/m at ambient temperature), where ρ_l is the liquid density, d_{drop} is the droplet diameter, V_0 is the impact velocity, and σ_l is the surface tension of deionized water. The capillary length $\lambda_c = \sqrt{\sigma_l/\rho_l g} = 2.7$mm. Owing to the characteristic radius of droplets smaller than the capillary length λ_c, the surface tension dominates the shape and droplets are spherical, with only a small dent at the bottom (Fig. 2(a)).

The wetting characteristics at ambient temperature were obtained with a goniometer. Fig. 2(a) illustrates the equilibrium wetting state of a droplet released at We ≈ 2 on the center area of the fabricated surface (a = 298 μm). When the maximum droop of the droplet is larger than the height of the pillar, the droplet contacts the bottom of the cavities between two pillars, namely, the droplet was in the Wenzel state. The red arrow in Fig. 2(a) shows the direction of increasing wettability gradient, namely, $\theta_1 > \theta_2 > \theta_3$. The contact angle firstly increases with the area fraction f ($f = a^2/[(a+l)h]$), then this trend gradually stabilizes. The curvilinear relationship between the contact angle hysteresis and the area fraction shows the effect of the wettability gradient on the droplet motion (Fig. 2(b)).

3. Results and discussion

Droplets placed onto the anisotropically structured surface at LFP are asymmetric in shape and the right part firstly detach from the hot surface (Fig. 3(b)). It is the gradient wettability on the surface that creates local energy barriers to induce the preferential droplet motion. The gradually increased area fraction of pillars is to control the surface wettability. The region of interest corresponds to the temperature of the surface above LFP. We conducted the experiment by holding $We \approx 2$ constant and changed the surface temperature ranging from 185 °C to 285 °C. Fig. 3(c) shows the directional transport of Leidenfrost droplets and the surface temperature was estimated to be 220 °C. It was observed that the droplet tended to move from the smaller superficial area of micropillars (SSAM) towards the larger superficial area of micropillars (LSAM).The roughness of the micro-/nanostructure can increase LFP by disturbing the formation of stable vapor layer [32–34] and can affect the flow field in which flow penetrates into the roughness cavities [35]. With increasing the surface temperature, the lifetime of droplets gradually increased. In our experiments, it was found that LFP to be higher in LSAM than SSAM and the vapor flow beneath droplets is more moderate in LSAM. The thickness of the vapor layer e depends on the relative size of droplets and the roughness [35]. The area fraction f is to revise the approximate formula of the thickness of the vapor layer proposed by Biance et al. [3]. The thickness of the vapor layer e relative to the scale of roughness yields

$$e \sim \frac{a^2}{(a+l)h}\left[\frac{\rho_l k_l \mu_l (T_w - T_{sat}) g}{h_{fg}\rho_v \sigma_l{}^2}\right]^{1/3}\left(\frac{d_{drop}}{2}\right)^{4/3} \tag{1}$$

where the film thickness e varies with the drop radius and the edge length a of pillars and we denote ρ_l as the density of the liquid droplet, κ_l the thermal conductivity of the liquid, μ_l the viscosity of the liquid, $(T_w - T_{sat})$ the difference between the surface temperature and the liquid saturation temperature, g the gravitational acceleration, h_{fg} the latent heat of vaporization, ρ_v the density of vapor,σ_l the surface tension of liquid drops and d_{drop} the droplet diameter, respectively. In our experiments, the diameter of droplets was set as d_{drop} = 1.13 mm. Therefore, the thickness of the vapor film is only associated with the parameters of the surface structure.

From pictures captured by the high-speed camera, the deformation and the droplet motion show an imbalance of the forces exerted on the droplet and the resultant force drives the droplet transport from SSAM to LSAM. Forces applied to droplets nclude: gravity G, supporting forces produced by the vapor film F_{v,x_i},F_{v,x_j} where the subscript v refers to properties of the vapor and x_i, x_j represent the positions of the supporting force