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Effect of different fluids on rectified motion of Leidenfrost droplets on micro/sub-micron ratchets

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ABSTRACT

Leidenfrost droplets, liquid droplets placed on a hot flat surface above the Leidenfrost temperature of the liquid, are an interesting model system to understand and achieve frictionless motion of droplets on a surface. Controlled unidirectional motion of otherwise random Leidenfrost droplets can be achieved by replacing the flat surface by a surface with topological ratchets. In this study, it is shown that an increase in the vapor layer thickness below the Leidenfrost droplet influences the droplet motion for underlying ratchets with various periods ranging from 1.5 mm down to 800 nm. This was exploited by systematically studying the Leidenfrost droplet motion of various liquids with low boiling points including acetone, isopropanol, and R134a on the aforementioned various ratchets. For all liquids with boiling points lower than water, no unidirectional motion was observed for 800 nm. This indicates that the asymmetric vapor flow beneath the Leidenfrost droplet becomes negligible due to the large vapor layer thickness relative to the ratchet depth. However, unidirectional droplet motion was still observed for the micron and millimeter scale ratchets even when the ratchet surface temperature was increased up to 360 °C and 230 °C for acetone and isopropanol, respectively. This can be attributed to the insulating property of the thick vapor layer which prevents the droplet from producing more vapor with increasing temperature. Also reported, is the effect of the ratchet period on the droplet motion at room temperature using R134a droplets.

1. Introduction

Liquid droplets placed on a hot flat surface above the Leidenfrost temperature of the liquid moves vehemently on the surface [1–3]. A vapor layer existing between the droplet and hot surface levitates the droplet from the surface, leading to a state where no friction at the drop-let/surface interface exists. The evaporation of the droplet is extremely slow due to poor heat transfer in the vapor layer. Such droplets are called Leidenfrost droplets and the temperature where the total evaporation time of a droplet is longest is defined as Leidenfrost temperature. Leidenfrost droplets are of great importance in many practical applications such as spray cooling in the heat treatment of metal alloys, impingement of oil drops on turbine engines, and re-wetting of fuel rod in nuclear reactor [4]. Recently, the Leidenfrost droplets have attracted significant research interest as a model system of non-wetting surfaces to understand and achieve extreme mobility of droplets without friction, similar to droplet dynamics on surfaces with superhydrophobicity [5–8].

Leidenfrost droplets on a flat surface usually show random motion, as can be observed when water is spilled on a hot frying pan. Control over the directionality of Leidenfrost droplets can be achieved by replacing the flat surface by a surface with topological ratchets. This phenomenon was initially demonstrated by Linke et al. with millimeter scale ratchets [9]. In their work, liquid droplets dispensed onto 1.5 mm period ratchets resulted in unidirectional motion with the droplet velocity in the range of several cm/s. The unidirectional motion was attributed to a viscous drag exerted by asymmetric vapor flow in the ratchet trenches. Following Linke's work, several research groups attempted to theoretically and experimentally reveal the driving mechanism relevant to this unidirectional droplet motion [10–14]. The Quéré group supported the viscous drag mechanism proposed by Linke et al. by showing that Leidenfrost solids directly sublimating on a hot substrate also self-propel by surface ratchets [10,11,13]. On the other hand, Würger et al. proposed using a Stokes hydrodynamics model in which thermal creep can be a mechanism to contribute to the unidirectional motion of Leidenfrost droplets on ratchet surfaces [14].

While all of the aforementioned work has been performed with millimeter scale ratchet surfaces, the length scale of this research was extended in our previous work to miniaturized ratchets with the period ranging from 1.5 mm down to sub-micrometers [15]. Interestingly, as the ratchet period decreases, the maximum velocity of water droplets dramatically increases, even reaching a droplet velocity larger than 40 cm/s with 800 nm period ratchets which has never been

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achieved with any chemical and topological gradient surfaces including millimeter scale ratchets. In addition, unidirectional motion is observed for all ratchet samples extending to the maximum temperature (360 °C) investigated.

Despite the achievement of such a fast droplet motion, our previous results [15] raised two additional questions. First, as the size of ratchets decreases, the velocity and the effective Reynolds number of the vapor flow in the ratchet valleys become smaller than those in the vapor layer between the ratchet peaks and the bottom of droplet, leading to reduction of net asymmetric flow of the vapor [14]. Therefore, the rectified droplet motion is expected to decrease and ultimately disappear. In contradiction, the Leidenfrost droplets still show an increase droplet velocity as the ratchet size decrease down to 800 nm in period. Second, due to the same reason, rectified droplet motion is expected to disappear as the vapor layer thickness becomes significantly larger than the ratchet depth, which is the case at a ratchet surface temperature significantly larger than the Leidenfrost temperature. However, the rectified motion is still observed at a ratchet surface temperature of 360 °C which corresponds to a vapor layer thickness of 50–100 μm [3]. Considering that the ratchet depth for 800 nm period ratchets is 200 nm, the results indicate that asymmetric vapor flow in such shallow ratchet valleys with nanometer scale depths can still produce drag force enough to induce a motion of droplet over the tens of micrometer thick vapor layer. Hence, it is interesting to examine the limitation on the unidirectional motion of Leidenfrost droplets driven by miniaturized ratchets, ultimately allowing for a better understanding of the driving mechanism.

In this study, in order to answer the aforementioned two questions, experiments were designed in such a way that the vapor layer thickness underneath Leidenfrost droplets relative to the ratchet depth are varied in a broader range than that used in our previous work [15]. Due to the difficulty in fabricating large area nanoscale ratchets, different liquids with lower boiling points than that of water were used in order to achieve a significantly larger vapor layer thickness underneath the droplet for an equal temperature to that of the water case. Our results show that the rectified motion of Leidenfrost droplets disappeared with sub-micron ratchets. However, the rectified motion was still observed for large ratchets even with the use of low boiling point liquids.

2. Experimental

2.1. Fabrication of nickel and brass miniaturized ratchets

Ratchets with periods ranging from 1.5 mm down to 800 nm (800 nm, 15 μm, 75 μm, 150 μm, and 1.5 mm) were fabricated in metals (either brass or nickel) and polymers (such as poly(methyl methacrylate) (PMMA)) using various micromachining techniques. Brass ratchets with micrometer scale period were produced via milling with a micromilling machine (KERN MMP2522, KERN Micro- and Feinwerktechnik GmbH & Co, KG, Germany) while nickel ratchets with 800 nm period were produced by replicating optical gratings and subsequent nickel electroplating. Details on the ratchet fabrication can be found in our previous paper [15]. The areas of the fabricated ratchet surface were 5×10 cm^2 for brass ratchets and 5.2×5.2 cm^2 for the sub-micron nickel ratchets. In order to investigate the effect of ratchet period, the ratchet aspect ratio, defined as the ratio of ratchet depth to period, was kept at a similar range (0.2 for micrometer scale brass ratchets and 0.25 for sub-micron nickel ratchets). To produce ratchets in polymers such as poly(methyl methacrylate), the fabricated brass or Ni ratchets were replicated via nanoimprint lithography. In order to study the influence of a hydrophobic coating on ratchet surfaces on the Leidenfrost droplet motion, some of the brass and nickel ratchets were coated by a fluorinated silane molecule, 1H,1H,2H,2H-perfluorodecyltrichlorosilane ($C_{10}H_4Cl_3F_{17}Si$) in a custom made chemical vapor deposition (CVD) chamber.

Prior to the study of impact and motion of droplet, morphologies of the fabricated ratchet surface were inspected using various metrology tools such as optical microscope, surface profilometer, scanning electron microscope (SEM), and atomic force microscope (AFM). Fig. 1 shows example SEM, AFM and optical micrographs for 75 μm and 800 nm period ratchets. The images clearly show the existence of topological asymmetric profiles. The root mean square roughness for the surfaces produced by the micromilling technique was typically 100–300 nm [16].

2.2. Investigation of Leidenfrost droplet motion

The experimental setup used to investigate Leidenfrost droplet motion consists of three parts: a hot plate for heating ratchet samples, a micropipette for injection of droplets, and a video camera for recording the droplet motion. For investigating the Leidenfrost droplet motion, a ratchet sample was placed on a digital ceramic hot plate (Isotemp, Fisher Scientific) at a set temperature. Once a constant temperature was achieved, an hour was allowed to elapse to ensure that thermal equilibrium was reached and proceeded to measure ratchet surface temperatures at four corners as well as at the center with a K-type thermocouple (TP 873/TP 882, EXTECH) and thermometer (ML720, EXTECH). The average temperature was used as the ratchet surface temperature. The accuracy of temperature measurements with the thermocouple and thermometer was ±0.3% according to manufacturer specifications. Usually, the difference between temperatures measured at the four corners is in the range of 0–15 °C. Droplets of a constant volume were then dispensed using a commercial micropipette (Eppendorf) with the volume in the range of 3–6 μL. The height of the pipette tip was manually controlled within the range of 2–5 mm from the ratchet surface. Various liquids including acetone, isopropanol and R134a were used.

Droplet trajectory was captured using a video camera (Sony DSC-V1, 16 frames per second) with the Windows Movie Maker (Microsoft) software for tracking and processing the captured videos. Since the acceleration of the droplet could not be properly monitored due to the

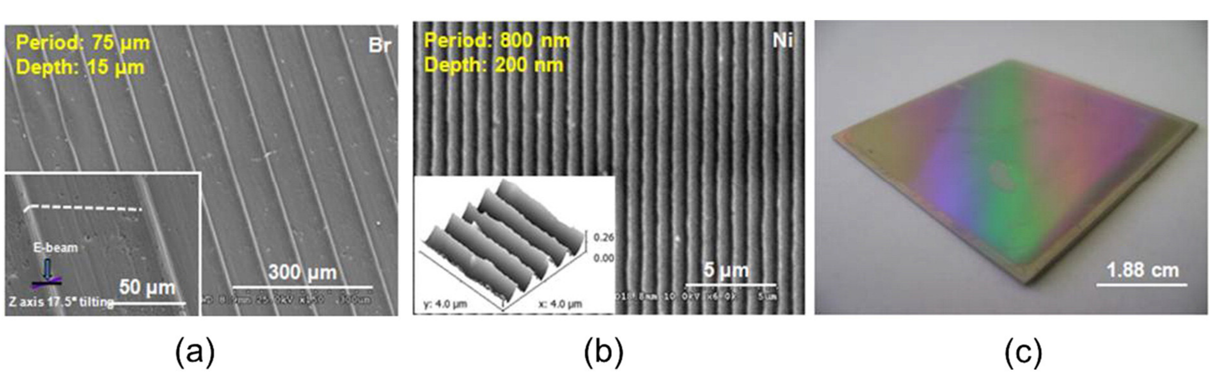

Fig. 1. (a) Scanning electron micrographs of micromilled brass ratchets with periods of 75 μm and (b) scanning electron and atomic force micrographs and (c) photograph of replicated nanometer scale ratchets with 800 nm period.