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IR laser caused droplet evaporation on the hydrophobic surface

Long Jiao, Rong Chen *, Xun Zhu, Qiang Liao

Key Laboratory of Low-grade Energy Utilization Technologies and Systems (Chongqing University), Ministry of Education, Chongqing 400030, China
Institute of Engineering Thermophysics, Chongqing University, Chongqing 400030, China

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ABSTRACT

In this work, the characteristics of the water droplet evaporation on the hydrophobic surface was visually studied, which was actuated by the photothermal effect of an infrared laser with the wavelength of 1550 nm. The interface temperature was measured by the infrared temperature measurement technique. The variations of the droplet geometrical parameters were captured, with which the evaporation rate was determined by the image process technique. Experimental results indicated that once the IR laser was applied, accompanying with the rapid increase of the interface temperature, the droplet evaporation was instantly induced. Generated vapor was condensed to form satellite droplets near the triple-phase contact line due to such a tiny local heating source that would not significantly change the surrounding temperature. After an increase in the contact radius and corresponding quick decrease of the droplet height, the original droplet gradually shrank. In this process, there existed a period with a relatively stable interface temperature and evaporation rate. In addition, the effects of the laser power and initial droplet volume were also explored. It was shown that both the interface temperature rising and average evaporation rates almost linearly increased with the laser power because more heat was generated by absorbing the light energy. Regarding the initial droplet volume, increasing the droplet volume firstly resulted in an increase in the interface temperature rising and average evaporation rates and then caused both of them to be reduced. The results obtained in this work are helpful for the future applications of droplet-based devices utilizing the photothermal effect.

1. Introduction

In recent years, the water and aqueous droplets with the small volumes are playing significant roles in many fields including micro-reactors, micro-fabrications, ink jet printing and so on [1–3]. Owing to its excellent advantages including quick and stable generation, flexible manipulation, diverse functions and simple fabrication of the substrate, the development of the droplet-based devices has attracted numerous interest from all over the world [4,5]. Among existing droplet-based devices, there are some new designs based on the phase change of the droplet, which greatly extends the functions of the droplet-based devices, such as particles deposition, biological detection, drug discovery, separation and extraction of products and so on [6–9].

Over the past decades, extensive efforts have been devoted to theoretical and experimental studies on the characteristics of the droplet evaporation [10–12]. As known, when water is exposed to the atmosphere, it evaporates because of the disequilibrium between the droplet and the surrounding, leading to the movement of the triple-phase contact line as well as the variation of the flow field in the droplet [13–16]. Many researchers have carried out the studies on the dynamic behaviors of the droplet evaporation with uniform heating source. For example, an experimental and theoretical study of the water droplet evaporation with the temperature difference of about 40 °C between the substrate and the atmosphere was performed by Gatapova et al. [17]. Three modes of the droplet evaporation, including constant contact radius mode (CCR), constant contact angle mode (CCA) and mixed mode were studied by varying the substrates. It was found that the evaporation rate was proportional to the contact radius. Trantum et al. [18] reported a biosensor that could be applied to the point-of-care diagnostics. Here the water droplet with the internal flow arising from the surface tension caused by the evaporation was used to concentrate the target particles aggregate in a detectable spot. Wong et al. [19] elucidated the physics of particle separation during the coffee ring formation based on a particle-size selection mechanism. These findings directly showed that the separation mechanism could be used to simultaneously separate and concentrate molecules, micro-organisms, and mammalian cells.

* Corresponding author at: Key Laboratory of Low-grade Energy Utilization Technologies and Systems (Chongqing University), Ministry of Education, Chongqing 400030, China. Tel./fax: +86 23 65102474.

E-mail address: rchen@cqu.edu.cn (R. Chen).

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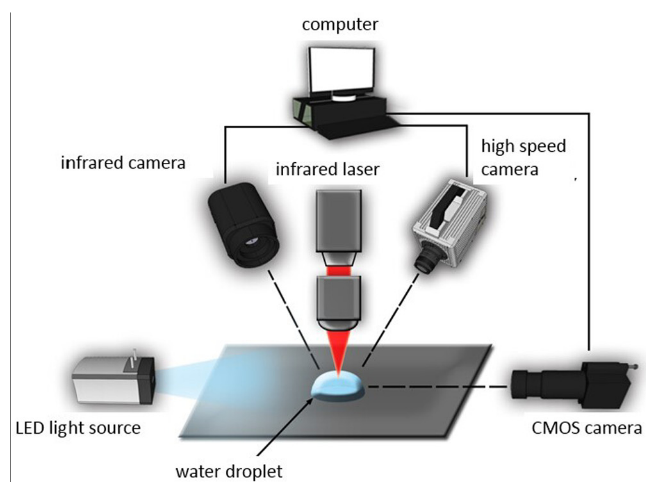
Su et al. [20] presented a miniature droplet reactor which allowed solid products to be easily collected by the droplet evaporation. In the traditional methods, however, the droplet evaporation usually adopts a passive way, which is hard to precisely control the evaporation process. Although some active control methods have been using the uniform heating source by patterning the heaters on the substrate or radiation heat transfer to the droplet, the evaporation process of the droplet could be significantly affected by serious thermal inertia. Hence, the sensitive and precise control of the droplet evaporation is needed.

More recently, the incorporation of optics into microfluidics results in the emergence of a new interdiscipline of optofluidics, which enables the non-contact manipulation of the fluids by using light [21,22]. The photothermal effect is one of the most important interactions between the light and fluids, with which the light energy could be converted into the thermal energy by photothermal materials or direct absorption [23,24]. Because light can be precisely controlled and easily focused to a spot with a small size of 100 μm or less, the photothermal effect is regarded as an ideal method to realize the local heating source. Right now, many photothermal effect based micro-devices have been developed [25,26]. Liu et al. [27] proposed a micro-pump system which utilized photothermal nanoparticles suspended in the water to convert the laser power into the heat. Using the photothermal effect induced evaporation–condensation–coalescence mechanism could continuously pump water. Boyd et al. [28] demonstrated a new method for the continuous chemical separation with the bubble-assisted interphase mass-transfer technique. Using the photothermal effect, Zhang et al. [29] proposed a bubble generation method in microfluidics where chromium pads were used as laser absorbing media. The focused light was converted to the heat by the photothermal effect, generating bubbles by the evaporation. However, although the photothermal effect has been successfully applied to microfluidic systems, few works have been reported on the combination of the photothermal effect with the droplet-based devices, which will be a promising method to realize quick and precise non-contact manipulation of the droplet evaporation. It should be pointed out that in conventional optofluidics, the photothermal effect usually needs the photothermal materials to complete the conversion of the visible light to the thermal energy [30–32]. Such design makes the system complex and inefficient. However, as a typical solvent in the chemistry and the biology, water has a strong absorbance to the infrared (IR) light. Therefore, the replacement of the visible light by IR light can make micro-devices simpler and more convenient to be operated. To date, only a few studies are focused on the direct use of the infrared laser to heat up a continuous water flow [33,34]. The droplet evaporation caused by the photothermal effect of the IR laser has not yet been studied. For this reason, to promote the incorporation of the photothermal effect of the IR laser into the droplet based micro-devices, it is essential to explore the droplet evaporation characteristics heated by the IR laser beam. Aiming at this target, the droplet evaporation induced by the photothermal effect of a 1550-nm infrared laser was visually investigated in this work. The dynamic behaviors of the droplet evaporation were studied by the image process and infrared temperature measurement techniques. Both the variations of the geometrical parameters of the droplet and the interface temperature were recorded. Particular emphasis of this work was directed to the determination of the evaporation rate. The effects of the laser power and the initial droplet volume were also investigated.

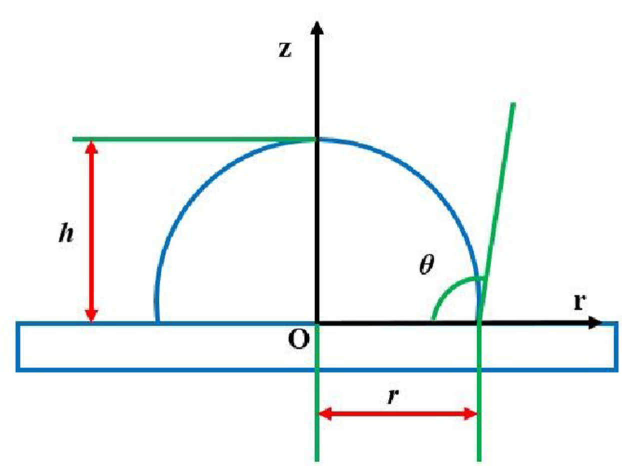
2. Experimental

In this study, the evaporation of a sessile distilled (DI) water droplet on a flat hydrophobic surface caused by the IR laser with the wavelength of 1550 nm was visually investigated. The flat hydrophobic surface was formed by coating a thin film of PDMS (polydimethylsiloxane, SYLGARD184, Dow Corning) onto a glass slide because PDMS is a hydrophobic material and has been commonly used in microfluidics due to its excellent properties of low cost, biocompatibility, nontoxicity and ease to fabricate. To do this, 5.6 g PDMS with the mass ratio of the base polymer and curing agent of 10:1 was firstly spin-coated on the surface of a silicon wafer at the rate of 700 rpm for 10 s and then dried at 90 °C for about 30 min. The thickness of the formed PDMS film was about 220 μm. Finally the flat PDMS film was bonded with the glass slide to form the hydrophobic surface.

With this hydrophobic surface, the experiments could then be performed. The experimental system is sketched in Fig. 1a. During the experiments, the droplets were generated by a syringe pump (Longer LSP02-1B) connected with a PTFE capillary tube with the inner diameter of 0.6 mm. At the other end of the capillary tube, a syringe needle was connected to generate droplets. By controlling the flow rate of the pump with the pumping time exactly equal to one minute for each droplet, the initial water droplets with desired volumes of microliters could be precisely generated and



(a)



(b)

Fig. 1. (a) Schematic of the experimental setup system and (b) illustration of the droplet profile.