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IR laser induced meniscus evaporation from a microchannel

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HIGHLIGHTS

- IR laser induced meniscus evaporation from a microchannel is studied.
- High laser power and small laser spot position yield high evaporation rate.
- Mass transfer coefficient at the interface is almost unchanged.

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ABSTRACT

In this work, the characteristics of the meniscus evaporation from a microchannel were studied, which was induced by the photothermal effect of the infrared laser with the wavelength of 1550 nm. The evaporation rate and mass transfer coefficient at the interface were determined by the proposed image process technique coupled with an infrared camera. Experimental results showed that once the infrared laser was applied, the interface temperature was rapidly increased but with non-uniform distribution as a result of such a tiny local heating source. Accompanying with the rapid temperature rise, the meniscus evaporation was also immediately actuated. After a certain laser heating period, the interface temperature was increased to a stable value with relatively uniform distribution. In the meantime, the evaporation rate increased and became steady. Besides, the effects of the laser power and laser spot position on the evaporation rate and mass transfer coefficient at the interface were also explored. It was shown that both the interface temperature and evaporation rate linearly increased with the laser power as a result of more heat generated. Smaller distance between the laser spot and front interface yielded higher interface temperature and evaporation rate because of smaller heat transfer resistance resulting from smaller transport length. Reducing the distance could make the increase of the evaporation rate to become more significant. With respect to the mass transfer coefficient, it is interesting to find that the mass transfer coefficients under all cases were almost the same, about 0.4 m/s.

1. Introduction

The advancement of micro/nanofabrication technology allows almost all functions of conventional chemistry and biology laboratories to be incorporated into a chip, forming so-called lab-on-a-chip or microfluidics, which promises to revolutionize many aspects of analytical chemistry and biochemistry (Harrison et al., 1992; Woolley and Mathies, 1994; Jacobson et al., 1994; Kamholz et al., 1999; Zheng et al., 2003). Such microsystem, which can deal with fluids geometrically constrained to micro or even nanoscale, offers several advantages over the conventional labs, including small reagent demand, short reaction time, precise control and manipulation and so on. Because of these advantages, microfluidics has been receiving ever-increasing attention and development in recent years. More recently, the incorporation of optics into microfluidics results in the emergence of a new interdiscipline of optofluidics, which leverages the advantages of both disciplines (Psaltis et al., 2006). Obviously, it is thus inherently concerned with the interactions between the optics and fluids as well as the dynamics of how both the optical and flow fields change in response to external stimuli (Erickson et al., 2005). Since there exist many interacted ways between the optics and fluids, this new technology of optofluidics has been applied in different areas, such as liquid micro-lenses (Krupenkin et al., 2003), microfluidic detectors (Adams et al., 2003), dye lasers (Galas et al., 2005).

The photothermal effect is one of the important interactions between the optics and fluids, by which the light energy can be converted into the thermal energy using photothermal materials or direct absorption. Moreover, light can be focused on a few hundred nanometers to micrometers so as to change the local

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properties of fluids, which is the scale demanded by analytical chemistry and biological applications. Hence, the use of the photothermal effect to design new microfluidics has realized many functions on a chip, such as the droplet microfluidics (Luo et al., 2013) and analyte manipulation (Akbari et al., 2010). In addition to these applications, the phase change caused by the photothermal effect has also created some new microdevices. With the focused light, the fluid temperature in a rather small illuminated region is quickly increased and in the meantime the temperature in other region remains unchanged, resulting in a rapid evaporation and condensation. Particularly, by moving the light focal point, the non-contact and precise manipulation of the locally interfacial phenomena can be realized. Many new microdevices that exploit the photothermally induced phase change have been developed and demonstrated. For instance, Hellman et al. (2007) demonstrated a laser-induced mixing strategy for microfluidic systems. In this work, a nanosecond pulsed laser was projected on the microchannel containing the parallel laminar flow of two fluids. The liquid in the focused area was rapidly evaporated because of the heat produced by photothermal effect, forming microbubbles. The bubble expansion and subsequent collapse within the microchannel disrupted the laminar flow of the parallel fluid streams and thus produced a quick mixing of two fluids. Liu et al. (2006) developed an optofluidic control method for pumping microflow using the suspended photothermal nanoparticles (PNPs). When a focused light illuminated the PNPs near the liquid–air interface, heat was generated and transferred from the PNPs to the surrounding liquid within tens of nanoseconds, which led to a rapid increase in the interface temperature and thus the evaporation from the interface. The vapor then condensed to droplets that were close to the interface. When droplets grew into larger ones that eventually coalesced with the original liquid body, the original liquid body could then be advanced. Instead of the suspension of PNPs in the liquid, PNPs could also be coated onto the inner surface of a microchannel (Boyd et al., 2008). When the PNPs were illuminated, the light energy could be absorbed by them and a bubble could be formed. With the assistance of the formed bubble and photothermal effect, the intra-mass transfer across the bubble was enabled, which could realize the chemical separation. Furthermore, Zhang et al. (2011) presented a unique bubble generation technique on microfluidic chips. In their work, a laser-absorbing chromium pad was built on the substrate of the microfluidic channel. This pad could strongly absorb the laser power and convert the focused light to heat by the photothermal effect so that a bubble was generated, which could be potentially applied to develop micro-valves and micro-pumps.

The above literature review indicates that the evaporation induced by the photothermal effect plays a critical role in the realization of these microdevices, whose performances are highly affected by the evaporation rate and mass transfer across the interface. In the past, extensive efforts have been devoted to the investigation of the phase change behaviors in microchannels. Wang et al. (2007) investigated an evaporating meniscus in a microchannel through an augmented Young–Laplace model, where the kinetic theory-based expression for mass transport across a liquid–vapor interface was derived. Dupont and Thome (2005) discussed the effect of diameter on both flow boiling heat transfer and transition from macro to micro channel. Kachel et al. (2014) investigated the evaporation of water from open U-shaped microchannel. The evaporation rates were measured using a new optical method and a gravimetric method. However, previous studies were mainly focused on the phase change resulting from the relatively uniform heat source. The conclusions drawn by these works may not be applicable for those photothermal effect based optofluidic microdevices, which share the unique feature of local heating. On the other hand, existing photothermal effect based microdevices usually employed photothermal materials to convert visible light to heat. However, as a typical solvent in chemistry and biology, water has a strong absorbance to infrared (IR) light (Curcio and Petty, 1951). The replacement of visible light by infrared light can make microdevices simpler. Hence, a few studies have been reported on the direct use of infrared laser to heat up water and the caused phase change (Xu et al., 2012; Fang et al., 2013; Liu et al., 2014). However, the characteristics of the evaporation caused by the photothermal effect still remain unclear. As a result, a deep understanding of the evaporation characteristics caused by the photothermal effect in microchannels is needed for optimizing the design and operation of these microdevices. Aiming at this target, in this work, the evaporation behaviors induced by the photothermal effect of a 1550-nm infrared laser were studied. Particular emphasis of this work was directed to the determination of the evaporation rate and mass transport coefficient at the interface. The effects of the laser power and laser spot position were also investigated.

2. Experimental

2.1. Microchannel fabrication

In this study, T-shaped microchannel with an open end was made by PDMS (polydimethylsiloxane, SYLGARD 184, Dow Corning) and formed by assembling two PDMS layers shown in Fig. 1a and then attached onto a glass slide. Here the ratio of the base polymer and the curing agent for PDMS was 10:1. During the fabrication process, the master molds were firstly fabricated by the standard photolithography process with SU-8 (photoresist, GM1075, Gersteltec Sarl) on a silicon wafer. The PDMS molds with the negative relief structure were then prepared by the casting process. Then two PDMS molds were packed together before they were completely solidified and coated on glass substrate. Then the microchannels were heated at 95 °C for 15–20 min. During the heating process, the thermal curing reaction of PDMS continued so that the two layers could be well bonded together to keep good adhesion between these two PDMS layers for the air tightness purpose. In this experiment, the mirochannel was 185 μm in height, 100 μm in width. At the open end, to avoid the effect of condensed droplets on the evaporation, a relatively large open microchamber with the length of 260 μm, width of 10 mm and

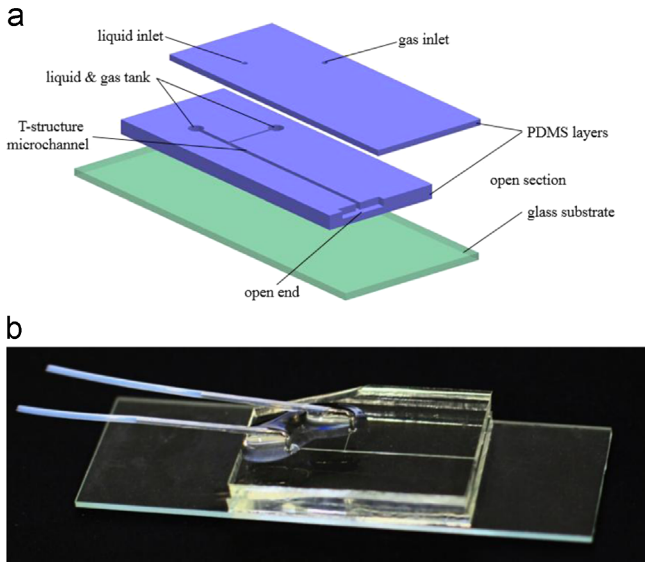

Fig. 1. (a) Schematic of the T-shape microchannel and (b) image of the fabricated microchannel.