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IR laser induced phase change behaviors of the NaCl solution in the microchannel

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HIGHLIGHTS

- IR laser induced phase change of NaCl solution in microchannel is visually studied.
- NaCl solution exhibits the distinguishing phase change behaviors.
- Dissolved ions lead to lowered temperature rise and evaporation rate.
- No coalescence between the condensed droplets and liquid slug is observed.

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ABSTRACT

With the promising potential in non-contact fluid manipulation, the photothermally induced phase change along with the interfacial behaviors have been frequently applied in various microfluidic devices. The property of the working fluid greatly affects the photothermal conversion and thus phase change behaviors. For this reason, the IR laser induced phase change of the NaCl solution in the microchannel was visually studied and compared with distilled water in this work. Experimental results indicated that the NaCl solution exhibited the distinct phase change behaviors. The existence of dissolved ions could weaken the photothermal conversion, leading to lowered temperature rise and evaporation rate as compared to the distilled water. In particular, different from the distilled water, the condensed droplets were formed at the region relatively far away from the evaporating interface due to lower evaporation rate. No coalescence between the condensed droplets and liquid slug was observed. Besides, the effects of the NaCl concentration, laser power and spot position were also investigated. It was found that higher NaCl concentration resulted in lower temperature rise and evaporation rate. With the increase of the input laser power and the decrease of the distance between the laser spot and the interface, the temperature rise and evaporation rate could be improved. The obtained results can be further applied in the design and operation of the microfluidic devices based on the photothermally induced phase change.

1. Introduction

Microfluidics has been rapidly developed in the past few decades. Because of its outstanding properties such as low reagent consumption, high specific surface area, and compact size, microfluidic devices and systems are widely applied in the fields of life science, chemical engineering, environmental detection (Gerlach et al., 2002; Livak-Dahl et al., 2011; Jokerst et al., 2012). In recent, the combination of optics and microfluidics brought new blood into the traditional microfluidic domain. Based on various interactions between fluid and light, multiple functions were implemented (Psaltis et al., 2006; Hunt and Wilkinson, 2007; Fan and White, 2011). As one of the most frequently utilized interactions between fluid and light, the photothermal effect has shown profound potential in local temperature control, thermal therapy and sensoring (Slyadnev et al., 2001; Huang et al., 2006; Schimpf et al., 2012; Luo et al., 2013), due to its attractive features, such as fast response and easy control. During the operation process of the microfluidic devices based on the photothermal effect, one interesting phenomenon is the photothermally induced phase change of the fluid in the microchannel. Accompanying with the

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interfacial behaviors, the photothermally induced phase change has become a promising tool for non-contact fluid manipulation. For example, Liu et al. (2005) reported a liquid actuation method based on the laser induced phase change in the microchannel. In their work, the photothermal nanoparticles were used to convert light energy into heat, and the photothermally induced evaporation-condensation-coalescence process provided a capillary driving force to pull the liquid forward in the microchannel. The photothermally induced phase change can also be triggered with the direct absorption of laser power by the working fluid (Yang et al., 2009; Ramirez-San-Juan et al., 2010; Xu et al., 2012). He et al. (2014) and Chen et al. (2016) studied the infrared (IR) laser induced phase change behaviors of distilled water in the microchannels. By changing the operation conditions of the IR laser, different phase change modes for fluid pumping and separation could be achieved, and the effect of the microchannel size on the phase change was also considered. Actually, except for the heating mode and geometric construction of the microchannel, the physical property and composition of the working fluid can also greatly affect the photothermal conversion between fluid and light and the subsequent phase change process. In particular, various types of working fluid (Lapotko and Lukianova, 2005; Lapotko, 2009; Zhang et al., 2011) were frequently used for the on-chip biological and chemical operations based on the photothermally induced phase change. For instance, Hellman et al. (2007) developed a method based on the photothermally generated cavitation bubbles for the solution mixing. Boyd et al. (2008) presented a laser triggered bubble-assisted interphase mass transport method for chemical separation in the microchannel, where the fluorescent dye solution was used as working fluid to monitor the separation process. However, previous works mainly focused on the device design and function implementation, few attentions have been paid to the effect of the working fluid on the photothermal conversion and phase change behaviors, which greatly affects the performance of the on-chip devices based on the photothermally induced phase change process. For this reason, the effect of working fluid on the IR laser induced phase change in the microchannel was investigated in this work. The NaCl solution, as a typical saline solution applied in the biological and chemical process, was chosen as the working fluid. To more clearly demonstrate the phase change characteristics of the NaCl solution, the IR laser induced phase change and interfacial behaviors of distilled water and NaCl solution were compared. Effects of the laser power, spot position and NaCl concentration were investigated. Results indicated the existence of the dissolved ions in the fluid influenced not only the photothermal conversion but also the phase change behaviors.

2. Experimental

The experimental system is shown in Fig. 1. An IR laser with the wavelength of 1550 nm was chosen as the heating source. The output fiber was coupled with a long working distance objective (10X Plan NIR, Mitutoyo), the laser beam was focused to a spot with the waist diameter of 30 μm and the focal length of 9 mm. The experimental microchannel was fixed on a 3-axis micro translation stage (LUGE, M150RX100Y100Z100-3, China), the main channel was set perpendicular to the laser beam with the beam axis through the microchannel. The step precision of the micro translation stage was 1 μm, so that the position of the microchannel could be adjusted to suit the focal plane of the focused laser beam. On the other side of the microchannel, a high speed CMOS camera (Point Gray, Grashoper3, Canada) connected with an adjustable zoom lens (Navitar, Zoom 6000, USA) was used to acquire real-time images in the microchannel. The focusing objective and the camera were placed on two individual manual translation stages to maintain the coaxality of the system during the experiment. The main measurements in this work were based on the image processing, and the zoom times and the image resolution of the camera were 500× and 2048 pixel × 2048 pixel, respectively. The image acquisition system provided a proportional scale of 1 μm/2 pixel to achieve an accurate spatial measurement. The maximum frame rate of the camera was 290 fps, which allowed us to record the transient phase change behaviors in the microchannel.

In this experiment, a liquid slug was generated in the microchannel for the study of the IR laser induced phase change and interfacial behaviors. The experimental microchannel was fabricated through standard SU-8 (SU-8 photoresist, Gersteltec Sarl, Switzerland) lithography and PDMS (Polydimethylsiloxane, SYLGARD 184, Dow Corning, USA) molding process. The T shaped microchannel was designed for the liquid slug generation by the shear interaction between the gas and liquid phases. The width and depth of the microchannel was 100 μm and 185 μm, respectively. Two syringe pumps were connected to the microchannel with the PTFE tubes for the liquid and air feeding, respectively. Before the laser was applied, the liquid slug was generated by controlling the liquid flow rate at 0.1 μL/min and the gas flow rate at 1 μL/min. The length of the liquid slug was controlled at about 1500 μm in all experiments, which was much larger than the spot diameter to ensure the local heating effect. When the liquid slug was located at desired position, the focused laser beam was then projected to the liquid near the gas-liquid interface to trigger the phase change. In this work, the temperature measurements were performed ex-situ by using a micro thermocouple (USA, Omega, COCO-001), which was embedded in the microchannel with the detecting joint located at the side wall during the PDMS casting process. The microchannel with the embedded micro thermocouple was only for the temperature measurement. It was meant that when measuring the working fluid temperature, the phase change behaviors would not be recorded. The phase change behavior induced by the photothermal effect was recorded by the microchannel with the same dimensions but without the embedded thermocouple. Such implementation could avoid the effect of the micro thermocouple on the phase change behaviors. A data acquisition unit (Agilent Keysight 34972A) was connected to the thermocouple to record the temperature variation. The corresponding temperature and time resolutions were 0.01 °C and 0.1 s, respectively.

In this experiment, the accidental error of the spatial and temperature measurement based on the image processing and ex-situ temperature measurement could be calculated by the following equation,

$$u_A = t \cdot \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n(n-1)}} \tag{1}$$

where $\bar{x}$ is the average value of the measurements, x_i is the measured value of a single testing, and n is the number of the measurements. All experiments were repeated three times in this work. The equipment error could be calculated by,

$$u_B = \frac{\Delta_e}{\sqrt{3}} \tag{2}$$

where Δ_e is determined by the measuring accuracy of the equipment. For the visualized experimental system, the value of Δ_e was 0.5 μm and the calculated equipment error was 0.29 μm. For the temperature measurement, the value of Δ_e was 0.01 °C and the corresponding equipment error was 0.06 °C. With u_A and u_B determined, the uncertainty of the experiment could be calculated,

$$\sigma = \sqrt{u_A^2 + u_B^2} \tag{3}$$