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Numerical investigation of the Marangoni convection during the liquid column evaporation in microchannels caused by IR laser heating

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ABSTRACT

In this study, the photothermal effect of an infrared laser induced evaporation and Marangoni convection of a liquid column in microchannels is numerically studied. The volumetric Gaussian heat source is used to model the laser beam and the shear stress at the vapor–liquid interface due to the surface tension gradient is accounted. The results show that under the same laser spot position and laser power, the evaporation mass flow rate in the hydrophilic microchannel is greater than that in the hydrophobic microchannel due to the small thermal resistance. The direction of flow patterns in liquid column are totally different since the relative magnitudes of the horizontal and vertical temperature gradients are opposite for these two surfaces. The effects of the laser power and spot position are also studied. It is found that as the laser power increases, the evaporation mass flow rate, evaporation heat ratio and strength of the Marangoni convection are all increased because more heat can be generated. Regarding the laser spot position, the evaporation mass flow rate and evaporation heat ratio both decrease with increasing the distance between the laser spot and interface because of increased thermal resistance. Moreover, the laser spot position can change the Marangoni convection roll both by the direction and magnitude. The results obtained are helpful for the design and operation of the microdevices with the photothermal effect induced phase change.

1. Introduction

In recent years, a wide range of studies on optofluidics which combines microfluidics with optics have been carried out since it was coined in 2003 [1,2]. Owing to its advantages inheriting from both disciplines, including small reagent demand, short reaction time and precise control, this new technology is favorable for biochemical applications [3–5]. In these applications, laser beams are commonly used because of high energy density, directivity and monochromaticity. Moreover, it can be easily focused to a tiny spot with microscale or even nanoscale, thereby enabling precise non-contact manipulation of fluids. In particular, there exist many interactions between the light and fluids so that optofluidics can realize different functions built-on a chip. Among these interactions, the photothermal effect is one of the important interactions in optofluidics, which can directly convert the light energy into heat. Based on the photothermal effect, several microdevices using photothermal materials or direct absorption have been proposed. For instance, Liu et al. [6] proposed an optofluidic micropump based on the mechanism of the evaporation–condensation–coalescence using photothermal nanoparticles suspended in the water to convert the laser power into heat. The magnitude of velocity could reach a few mm/s by this micropump. Matthieu et al. [7] also achieved the directional flow under infrared (IR) laser induced thermocapillary interaction with a microfluidic droplet generator. Zhang et al. [8] proposed a bubble generation method in microfluidic chips using the laser induced heat, where chromium pads were used as laser-absorbing media. Xu et al. [9] have also investigated the evaporation characteristics caused by the photothermal effect of an IR laser in microchannels.

It can be found that existing microdevices based on the photothermal effect usually involve the phase change process. In this context, the performances of these microdevices are highly affected by the evaporation rate and dynamic behavior at the interface and fluid flow and heat transfer in the liquid phase. When the laser heats up the liquid near the interface in a small illuminated region, the temperature at the interface can be instantly increased, leading to the evaporation. Simultaneously, since the laser is a typ-

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ical tiny heating source, which can create the non-uniform temperature profile at the interface. Hence a surface tension gradient is formed, which can result in the shear stress driving liquid from low surface tension region to high surface tension region along the interface. Such dynamic interfacial behavior is known as Marangoni convection [10]. As a result, it can be known that the coupling of the photothermal effect induced evaporation and Marangoni convection plays a major role in these microdevices. In the past, much attention has been paid to the Marangoni convection analysis during the evaporation both by experiments and simulations. Dhavaleswarapu [11], Lan et al. [12] and Wang et al. [13] discussed the Marangoni and buoyancy effects on the flow field near an evaporating meniscus. Sim and Zebib [14], Simic-Stefani et al. [15], Serpetsi and Yiantsios [16] focused on the oscillatory Marangoni convection in cavities. In their work, the Marangoni number specified the critical condition for the onset of oscillations. In addition, Ward et al. [17], Duan et al. [18] and Song et al. [19] have also visualized and characterized the Marangoni convection in water, and calculated the evaporation mass flow in a small vacuum chamber.

Despite the Marangoni convection resulting from the spontaneous evaporation of the volatile liquid has been widely studied, the works on the coupled evaporation and Marangoni convection caused by the laser heating in a microchannel has not been reported yet, which is a typical phenomenon in optofluidics [6,20,21]. Because of such a tiny local heating source, it can be known that some rather distinct behaviors may be caused. As a result, it is necessary to shed light on the characteristics of the Marangoni convection and evaporation actuated by the laser heating. Aiming at this target, the present work is to develop a three-dimensional model to simulate the fluid flow and heat transfer inside a liquid column in microchannels accompanying with evaporation induced by the laser heating. In this study, water is chosen as the working fluid since it is a typical solvent in chemistry and biology. Meanwhile, an IR laser with the wavelength of 1550 nm is used to heat up water directly because water has a strong absorbance to IR light [22]. The effects of the wettability and laser power and position are also investigated.

2. Model development

2.1. Model description

The physical model is shown in Fig. 1. A liquid water column is pinned in the microchannel with the aspect ratio of width to length $d_0/l_0 = 1/5$. The length of liquid column used in this work is acceptable since the distance between the heat source and the interface is more significant than the length of the liquid column. In addition, the previous work [13] has also confirmed that the aspect ratio of 1/3 for the liquid column shows less effect on the evaporation. Hence, the aspect ratio of the microchannel is chosen to be 1/5 for all study cases. A continuous IR laser beam with the wavelength of 1550 nm is illuminated to the liquid column near the interface. Due to the photothermal effect of the IR laser, the light energy is converted into heat, leading to the temperature increase. Under such a circumstance, not only the evaporation at the interface but also the Marangoni convection in liquid column are caused. In this work, the simulated energy density of the IR laser is assumed to follow Gaussian distribution and can be expressed as [23],

$$q_v = \begin{cases} 0 & r > w_z \\ \frac{Q}{\pi w_z^2 h} \exp\left(-\frac{r^2}{w_z^2}\right) & r \leqslant w_z \end{cases} \tag{1}$$

where Q is the laser power (W), h is the absorption height and equal to the microchannel depth of 100 μm in this simulation. r is the horizontal distance of the point (x, y, z) to the center line of the laser beam located at the plane $x = 50$ μm. w_z is the laser beam radius (radius of Gauss function curve), which can be given by,

$$w_z = w_0\sqrt{1 + \left(\frac{z - 5e^{-5}}{z_R}\right)^2} \tag{2}$$

where z_R is the Rayleigh length of the IR laser, w_o is the waist radius of laser beam. In this study, $z_R = 50$ μm and $w_0 = 10$ μm for all cases. The light energy absorbed by water to be converted into heat, $q_{v,\text{liquid}}$, can be calculated by,

$$q_{v,\text{liquid}} = \eta q_v \tag{3}$$

where the heat absorption rate $\eta = 1 - e^{-\alpha h}$ and $\alpha = 10.9\ \text{cm}^{-1}$ is the absorption coefficient of the IR laser with the wavelength of 1550 nm in water [21,24]. The heat absorption rate of water is then equal to 0.103 for all cases. Because the size of the microchannel is rather small, such a small space easily makes the air in the vapor space to be saturated at room temperature during the evaporation process. Hence, the vapor space in the microchannel is assumed to be saturated. When the IR laser is projected to the liquid column, the temperature at the interface will be quickly increased because of the photothermal effect and short distance between the laser beam and interface, leading to the water evaporation and non-uniform temperature distribution across the interface. Such a non-uniform temperature distribution leads to the surface tension gradient at the interface so that the resulting Marangoni convection drives the liquid to flow from the warm region to the cold region. The heat flux due to the evaporation and the shear stress at the water–air interface will be illustrated in the following.

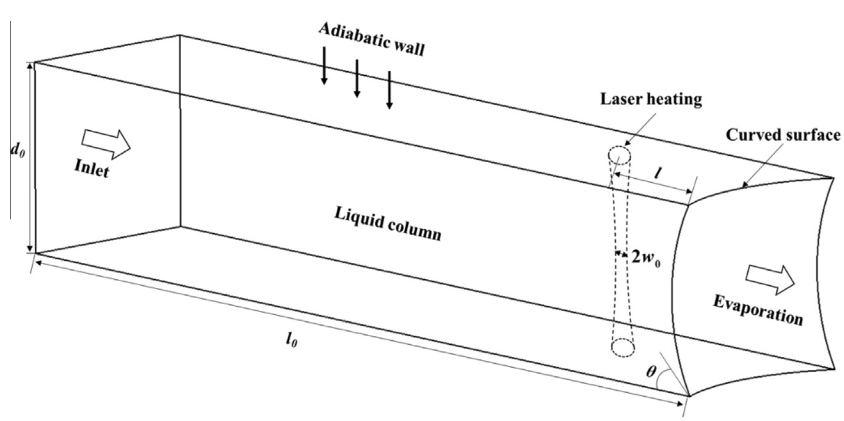

Fig. 1. Schematic diagram of the three-dimensional physical model.