Colloids and Surfaces A: Physicochem. Eng. Aspects xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Colloids and Surfaces A: Physicochemical and Engineering Aspects

journal homepage: www.elsevier.com/locate/colsurfa

Droplet formation caused by laser-induced surface-tension-driven flows in binary liquid mixtures

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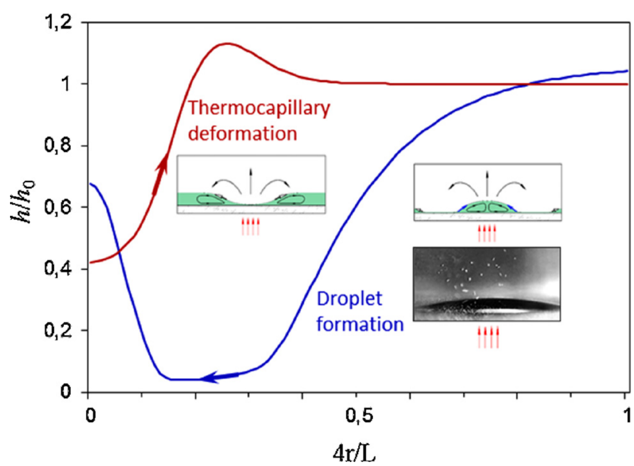
HIGHLIGHTS

- Model for the laser-induced droplet formation mechanism in binary mixtures is proposed.
- Droplet formation is controlled by solutocapillary inflow of mixture and evaporative outflow of volatile component under laser heating.
- Droplet growth rate depends on the initial concentration of components in mixtures.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 25 April 2016
Received in revised form 1 July 2016
Accepted 2 July 2016
Available online xxx

Keywords:
Marangoni convection
Droplet microfluidics
Light-driven microfluidics
Binary mixtures

ABSTRACT

Experimental and numerical study of the droplet formation mechanism in thin layers of water-isopropanol mixtures under the laser heating is presented. It is shown that after the beginning of the irradiation the thermocapillary convection dominates that result in the thinning of the layer in the heated area due to the flow of liquid into the cold area. In a few seconds, the loss of isopropanol in the heated area due to evaporation become significant that produces solutocapillary convection with the opposite directed flows. As a result, a droplet appears in the laser beam and continuously grows owing to the solutocapillary liquid flow through the wetting film between the droplet and the receding layer. The experimental results indicate that an increase in the initial concentration of isopropanol in mixture leads to a decrease in the droplet growth rate at a given power of the laser beam. A numerical model of the droplet formation process is proposed. The evolution of the liquid-gas interface is modelled in the frame of lubrication theory including the dependency of surface tension on both temperature of mixture and concentration of volatile component. The model takes into account the dynamics of the vapor in the gas phase including the convective and diffusion mechanisms. A reasonable agreement between the numerical and experimental results is shown.

1. Introduction

Marangoni convection caused by concentration surface tension gradients is frequently encountered phenomena in a large variety

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http://dx.doi.org/10.1016/j.colsurfa.2016.07.004
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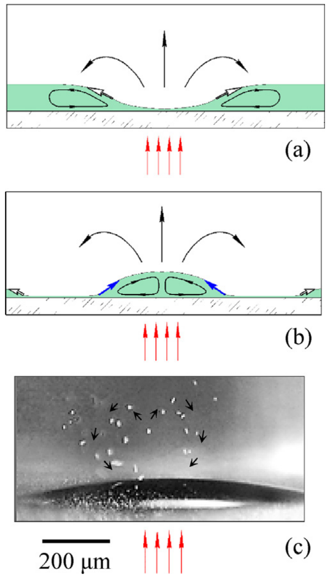

Fig. 1. Schematic diagram of the laser-induced droplet formation process in a closed cell. (a) Thermocapillary spreading of the liquid and evaporation of volatile component from the irradiated area; (b) the droplet formation caused by centripetal solutocapillary flows towards the irradiated area; (c) an experimental snapshot of the droplet formed in the laser beam, white spots—the condensed vapor droplets circulating above the droplet (the direction of circulation is shown by black arrows).

of material science applications, including laser machining, surface micromodification and texturizing [1–5], solidification and melting processes [6,7], Marangoni drying [8,9], heat pipe technology [10] and the crystal growth process [11]. In many cases, the action of solutocapillary forces leads to the formation of features resembling droplets or bumps [1–5], which can be used in tribological applications [2,4,5].

The droplet formation and manipulation is of a great importance in digital microfluidics, which is a promising technology for conducting biological and chemical assays in lab on chips [12,13]. Despite variety of methods developed for the droplet manipulation, including optoelectrowetting [14,15], thermocapillary [16,17] and photochemical wettability [18], the formation of droplets at controlled rates with strictly specified sizes and controlled concentration of reagents remains the challenging problem in microfluidics. In most cases, droplets are formed by electrowetting splitting of relatively large liquid samples [12,19] or by injecting immiscible fluids into T-junction or the flow focusing [13] microchannel configurations. Earlier authors [20–23] have proposed an alternative way for the droplet creation and manipulation based on using the light controlled solutocapillary phenomenon [24,25]. This phenomenon is observed in thin layers of light–absorbing liquid mixtures of a low volatile positive tensioactive liquid and a high volatile liquid with low surface tension. The positive tensioactive liquids increase the surface tension of solutions (for instance, adding water in alcohols). When the light beam heats the layer of such mixture, surface tension decreases and liquid spreads due to the thermocapillary stress (empty arrows, Fig. 1a). This process is accompanied by local evaporation of volatile liquid and consequently decreasing its concentration in the irradiated area. The latter process results in an opposite directed surface tension gradient related to concentration (solid arrows, Fig. 1b). When the concentration surface tension gradient starts to dominate over the thermal surface tension gradient, the centripetal solutocapillary flows arise. The solutocapillary flows lead to an accumulation of mixture in form of a solitary droplet in the irradiated area (Fig. 1b). Fig. 1c illustrates an image of a droplet formed in a thin layer of water isopropanol mixture with a laser beam (a side view). White spots observed above the droplet in Fig. 1c are tiny droplets of condensed vapor, which demonstrates convection in a gas phase. The arrows show the direction of convective motion.

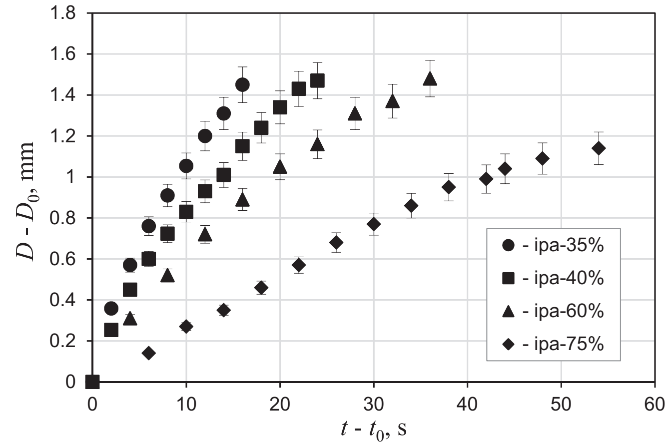

Fig. 2. Time evolution of the droplet diameter in the mixtures with different concentrations of isopropanol during the continuous heating with the laser beam.

Interestingly that this effect is similar to the well-known classical phenomena such as “tears of wine” [26,27] and Skogen effect [28]. In both of them, the convective motion of liquid and consequently a bump formation is caused by the surface tension gradients due to either spontaneous evaporative-driven gradients in alcohol concentration [26,27] or due to a locally burning out of surfactants on the free water surface [28].

Here we report investigation of the droplet formation process caused by the laser beam in thin layer of mixtures of water and isopropanol at different concentrations. The focus is put on numerical modeling of the studied phenomenon, which is supported by the experimental results. The current model extends our recent work [23] to include the effects of two-dimensional variation of vapor density in a gas phase, as well as the variation of the concentration of volatile component in liquid layer caused by evaporation.

2. Experimental method and results

An experimental study of the droplet formation process has been carried out using binary mixtures of distilled water and isopropanol at concentrations of isopropanol varying from 35 to 75 (w/w)%. Distilled water is the positive tensioactive liquid and isopropyl alcohol is a volatile component. Mixtures contain Brilliant Green dye to ensure the absorption of the laser irradiation. A layer of binary mixture with thickness of 100 ± 20 µm resides in a closed Petri dish with a radius 2 cm. A semiconductor laser beam with a wavelength of 659 nm and a power of 18 mW impinges the absorbing mixture layer resulting in solutocapillary flows and the droplet formation. The power of absorbed laser irradiation by 100 µm layer of mixture measured with the laser power meter (Nova Ophir, working range 60 µW to 3W, Ophir Photonics, Ltd) is around 8 mW. Using the Beer-Lambert law the linear absorption coefficient is calculated to be $\lambda \cong 10^4\,\text{m}^{-1}$. The droplet formation process is observed from above with an optical microscope equipped with CCD camera (Baumer, Germany). A temporal variation of a droplet diameter $D(t)$ is traced on captured images during 1 min. An average error of the droplet diameter measurements is less than 10%.

It is observed that the droplet appears in the irradiated area within a few seconds after the beginning of the irradiation. During this time (designated as t_0) in mixtures with the high concentration of isopropanol, the thermocapillary spreading of the liquid results in a significant thinning of the layer in the heated area, where after then the droplet with an initial diameter (D_0) appears. This

Please cite this article in press as: K.A. Tatosova, et al., Droplet formation caused by laser-induced surface-tension-driven flows in binary liquid mixtures, Colloids Surf. A: Physicochem. Eng. Aspects (2016), http://dx.doi.org/10.1016/j.colsurfa.2016.07.004