Numerical Simulation on the Influence of the Properties of Continuous Phase on Fluid Flow and Temperature Response in a Laser-Heated Suspended Droplet

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Extended abstract: With the advances in micro total analysis systems (μTAS), the droplet-based microfluidics, which manipulates mini discrete droplets in an immiscible continuous phase to accomplish various detections, has been applied to many fields including medicine, pharmacy, fine-chemistry and biotechnology as it offers distinct advantages, such as small diffusion length, high-throughput, precise control and integratability [1]. As compared to the continuous-flow microfluidics, the samples in the droplet-based microfluidics are isolated by a defined droplet/continuous phase interface, avoiding the cross contamination and resulting in a controllable reaction environment. In the droplet-based microfluidics, the control of the droplet temperature with prominent temporal spatial resolution is considered to be significantly important for the specific biochemical analyses. For instance, polymerase chain reaction (PCR), which has been widely used to amplify target DNA with several orders of magnitude for the follow-up analysis, highly depends on precise adjustment of the droplet temperature to realize the repeated thermal cycles [2].

Recently, the photothermal effect, by which the light energy could be converted into the heat of the suspended droplet, has exhibited significant potentials in flexible and precise temperature control owning to non-contact state, prominent tenability and high accuracy [3]. Notably, due to the wonderful configurability of the light, dynamic beams could be patterned so that thousands of optical pixels could be generated by the light modulators to provide the simultaneous control of thousands of suspended droplets in the continuous phase, significantly promoting the throughput. In addition to the light energy conversion, the properties of the continuous phase in the photothermal effect-dominated droplet-based microfluidics, such as the viscosity, thermal conductivity, specific heat, thermal expansion coefficient and boiling point, would also significantly influence the fluid flow and heat transfer occurring in droplets but the underlying mechanisms remains unclear. Therefore, it is significantly essential to elucidate the influence of the properties of the continuous phase on the fluid flow and temperature response in a laser-heated suspended droplet.

To this end, we numerically study the characteristics of the fluid flow and heat transfer of a laser-heated suspended droplet in the immiscible continuous flow. Because the viscosity and thermal conductivity are two of the most important factors affecting the fluid flow and heat transfer, the main objective of this work is devoted to the real-time temperature distribution and Marangoni flow in a laser-heated suspended droplet under different viscosities and thermal conductivities. In this model, the physical model is reduced to two dimensions with the axial symmetry and two fluids simulated are water (droplet) and oil (continuous phase),

respectively. The droplet with the diameter of 100 μm is placed at the origin. The length and the height of the calculation domain are 1000 μm and 500 μm, respectively. The laser power and the laser diameter were 30 mW and 40 μm, respectively. Prior to the model development, there are some assumptions to be made: (1) There is no mass transfer through the droplet interface; (2) The water and the oil are both treated as the incompressible Newtonian fluids; (3) The droplet interface has no deformation; (4) The fluid flow is laminar flow. Based on these, the governing equations consisting of the continuity, the momentum and the energy equations can be achieved. The volumetric Gaussian heat source (TEM_{00}) is used to model the laser. The heat transfer coefficient, the Nusselt number (*Nu*) and the Marangoni number (*Ma*) are analyzed. The simulation is implemented using ANSYS Fluent 14.5. Besides, the water viscosity is changed with the local temperature while the variation of the oil viscosity is neglected. The variation in the surface tension is considered by the dependence of the surface tension coefficient with the temperature.

The simulation results indicate that when a suspended droplet in the continuous phase is heated by a focused laser, the inhomogeneity of the temperature distribution is formed, resulting in the surface tension difference across the interface and thereby the Marangoni vortexes. The results also show that the higher the viscosity of the oil is, the weaker the flow in the continuous phase is. Thus, the heat transfer coefficient at the droplet interface is obviously reduced, resulting in the higher increase of the average temperature. Meanwhile, *Nu* is decreased, promoting the homogeneity of the droplet temperature, as shown in Fig. 1(a). The non-uniform temperature coefficient, which is defined as the difference between the maximum interface temperature and minimum interface temperature over by the average temperature rise of the droplet, is apparently decreased. Moreover, with the larger average temperature increase, *Ma* is increased due to the decrease of the water viscosity. It is found that with higher thermal conductivity of the oil, more heat is transferred to the surroundings, resulting in larger heat transfer coefficient. Therefore, the average temperature increase of the suspended droplet is decreased (Fig. 1(b)). For the same reason, the temperature response time is decreased with increasing the thermal conductivity of the oil. Simultaneously, with the rapid decrease of the average temperature rise, the non-uniform temperature coefficient is apparently increased. In addition, it is also found that the trend of *Ma* is first increased and then decreased with increasing the thermal conductivity of oil because of the coupling effect of the surface tension change and the temperature-changed water viscosity.

These simulation results are helpful for future development of the temperature regulation in a laser-heated suspended droplet, promoting the implementation of the droplet microfluidics based on the photothermal effect.

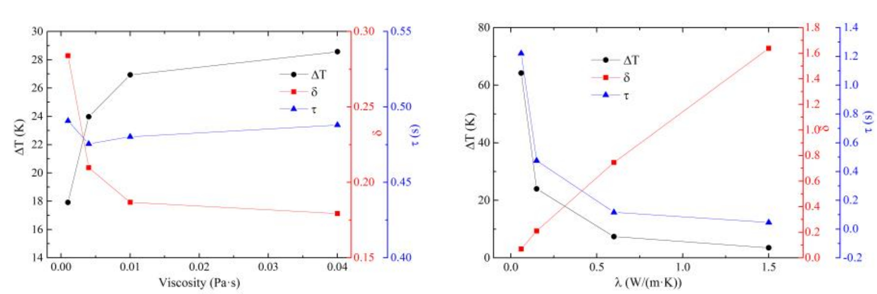

Figure 1: The variations of the average temperature rise, the non-uniform temperature coefficient and the response time with (a) the viscosity and (b) the thermal conductivity of the continuous phase

Keywords: Suspended droplet; Continuous phase; Photothermal effect; Viscosity; Thermal conductivity; Temperature response

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