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Size Effect on Micro-Droplet Movement due to Marangoni Effect

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ABSTRACT

Fundamental physics are studied on the movement of droplets for sizes ranging from 0.1 $\mu\ell$ to 1.0 $\mu\ell$ on a solid surface subjected to temperature gradients using numerical computations and the comparison with experiments. The receding/advancing contact angles relating to the droplet size and shape are the key parameters of droplet moving and the differences subjected to the temperature gradients induce unbalanced recirculation zones inside the moving droplet, thus induces driving force to drag the droplet. It is found that droplet of smaller size moves faster with smoothly changing speed and the droplet of larger size moves with fluctuating speed and the average moving speed is roughly the same magnitude as that with two-dimensional heating.

INTRODUCTION

As the liquid droplet in microscale size, surface tension is the major driving force to pump the droplet in motion without any moving parts in a device. For example, Burns et al [1] developed thermocapillary pumping to drive the droplet in motion inside a microfabricated flow channel by generating temperature difference and creating surface tension difference on two ends of the liquid drop. Kataota et al [2] produced significant microscopic liquid film flow on a selectively patterned surface even by small thermal gradient. Numerous approaches have developed and demonstrated to move the micro-liter liquid droplets on the solid surface. The driving mechanisms for moving droplets on solid surfaces include electrostatic actuation [3,4], electrowetting on dielectric [5], light-drven [6], gravitational field for liquid marbles [7], surface tension gradient resulting from the phase change [8], asymmetrically structured surfaces [9], etc. This paper studies the sizes effect on the movement of micro-liter droplets on a solid surface subjected to temperature gradients using first principle equations to reveal the physical mechanism through the receding/advancing contact angles and velocity fields and the comparisons with records by high speed CCD camera.

EXPERMINITAL SET-UP [10]

The silicone oil droplets with sizes of 0.1, 0.5, 1.0 and 2.0 $\mu\ell$ are dispensed by a pipette on a solid surface of glass substrate coated with Teflon film. Teflon coating increases the surface tension as well as the contact angle between solid surface and silicone oil. Microheaters manufactured using MEMS technologies are fabricated and embedded on the solid surface to generate temperature gradients. A series of distributed microheaters made of Pt/Ti produce temperature gradients up to 95°C/mm (Fig.1). Fig. 2 plots the temperature distributions in axial directions for the experiments. The droplet moves as it is subjected to the existing temperature distribution and the moving pictures are recorded by CCD camera with 360 frames/sec.

NUMERICAL SIMULATIONS

Numerical simulations solve conservation equations of mass, momentum and energy. The two-phase flow calculations employ homogenous flow model with Volume-of-Fluid (VOF) interface tracking methodology [11] and Continuum Surface Force (CSF) [12,13] model. These first principle equations provide detailed temperature distributions and velocity distributions inside droplets as well as advancing/receding contact angles for the micro-droplet. Three simulation cases are performed, 0.1$\mu\ell$ and 1.0$\mu\ell$ droplets moving one a heated area of 1mm (x-direction) by 2mm, 1.0$\mu\ell$ droplet moving on a heated area of 1mm by 3mm (reference to the top illustrations of Fig.4). The temperature distribution along x-direction is set as the one measured in the experiment. Since the base diameters for 0.1$\mu\ell$ and 1.0$\mu\ell$ droplets are 1mm and 2.17 mm, two-dimensional distribution of temperature field is encountered for the 1.0$\mu\ell$ case. Therefore, two-dimensional effect on the droplet shaping and moving can be obtained at the same time.

RESULTS AND DISCUSSION

The displacement histories of the droplet moving are recorded by the high-speed camera (Fig.3)[10] and thus the histories of droplet moving speed and receding/advancing contact angles can be digested (Fig.4). The droplet experiences an abrupt jump of the initial speed as the liquid front overcomes a threshold drag energy by the unbalance of surface and kinetic energy across the droplet, then the moving speed increases to a peak value at 0.5-0.7 sec and then decreases to zero at 9, 20, 20, and 20 sec for droplet sizes of

0.1, 0.5, 1.0, and 2.0 μℓ, respectively (Fig.4). The maximum velocities of front/tail ends of the droplets are 0.65/0.78, 0.66/1.08, 0.78/1.24, and 0.48/1.23 mm/s for 0.1, 0.5, 1.0, and 2.0 μℓ droplets. The droplet movement involves the shape change due to the change of receding/ advancing contact angles, and the advancing contact angle increases up to 84°, 82°, 78°, 70° with receding contact angles at 60s' as the droplet moves while the static contact angle is 52° for silicone oil on Teflon surface. The limited information from the experimental observations implies the need of first principle simulation so that the fundamental physics of the droplet moving can be observed.

Numerical simulations of sequential pictures of a moving silicone-oil droplet with volumes 0.1 and 1.0 μℓ on heating areas of 1mm by 2mm and 1mm by 3 mm (Fig.5a, 5band 5c) are displayed. The temperature distributions shown by the gray levels on the changing shaped moving droplets provide the quantitative and qualitative physics and moving power from the surface tension. The 0.1μℓ droplet stays the same position for some time while the droplet changes shape and generates a net thrust force to move the droplet for a period of time, then the droplet stops to move at flat temperature gradient (Fig.5a). For the 1.0μℓ droplet, some warm-up time is also observed, but the moving speed picks up after some time but the magnitude is oscillating to balance the changes of droplet shape. In general, larger droplet moves with slower speed. The moving speed is roughly the same as the heating area is increased to 1mm by 3mm, but the droplet shape is changed somewhat (Fig 5c). Since moving speeds at leading and trailing edges are different with different advancing /receding contact angle, the droplet shape changes accordingly. The moving speeds at advancing and receding edges can be characterized parameters of the moving droplet. Figures 6a to 6c plot these velocities for 0.1μℓ and 1.0 μℓ droplets on heating surfaces of different sizes and illustrate the moving hsitories. In addition to show the increase of moving speed, fluctuating velocity during the moving history is clearly shown for droplet of increased size (Fig.6b) due to inertial effect. The velocity histories are varied in pattern with similar magnitude if the heating area shape goes nearly one-dimension, which implies the limited three-dimensional effect in this scale (Fig.6c). Although measured and computational histories of droplet moving are in different time span, they tell the same stories of the droplet moving basically.

The conversion of thermal energy to kinetic energy can be translated by the velocity distributions inside the droplet and the surrounding air during moving. Therefore, the velocity distribution is of interest. Figure7a shows the top view and vertical cutting plane of velocity vector plots for various sized droplet on different heated zones. The figures indicate that there is a singular point in the center and flow circulates from the bottom surface to the top of the droplet via temperature difference as the droplet stays stationery (Fig.7a-1, Fig.7b-1, and Fig.7c-1). The singular point moves to the front toward moving direction as the droplet moves, which means that a larger circulation zone on the back side than the one on the front side as the overall velocities moves to the leading direction (Fig.7a-2, Fig.7b-2, and Fig.7c-2). Two recirculation zones go to the same size and the overall velocity vectors are balanced as the droplet stops moving (Fig.7a-4, Fig.7b-4, and Fig.7c-4). Comparing, Figs. 7a-7c, it is found that the velocity vector patterns are similar although the droplet shapes are deformed in somewhat different shapes. It implies that the small effect of two-dimensional heating is observed.

CONCLUSION

Basic physics of droplet moving on solid surface subjected to temperature gradient are the same for droplet of different sizes. The balance of surface tension and the velocity vectors inside droplet determines the movement of the droplet and the mass and temperature gradient across the droplet volume dictate the movement. Oscillating or fluctuating moving speed is observed for droplets of large size due to the inertial effect and shorter moving duration but fast moving speed are observed for droplets of small size.

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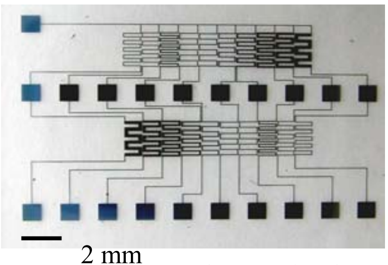

Fig 1. OM Micrography of Microheaters

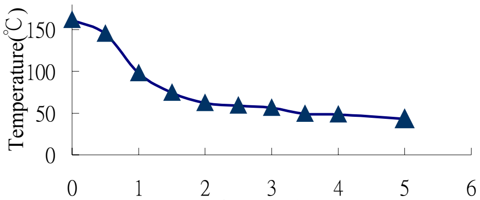

Fig 2. Temperature Profile Pescribed

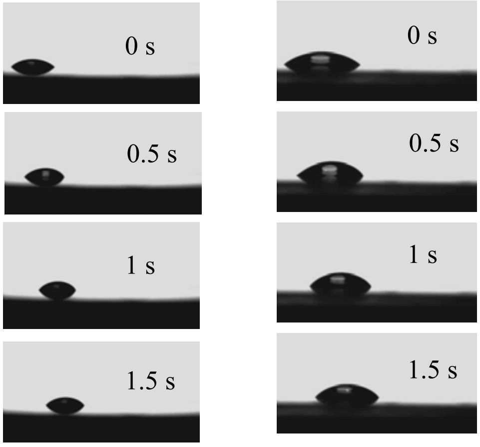

Fig 3. Displacement Histories of the Droplets of (a) 0.1μ*l* (b) 1μ*l* [13]

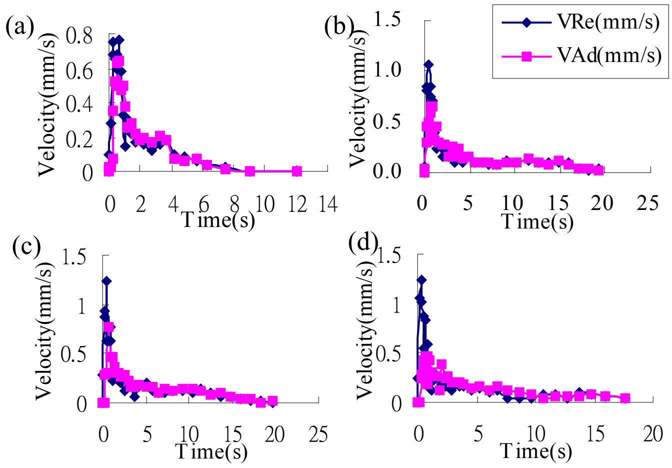

Fig 4. Observed velocity histories for microdroplet movement on the prescribed temperature distribution for droplet sizes (a) 0.1μℓ, (b) 0.5μℓ, (c) 1μℓ, (d) 2μℓ

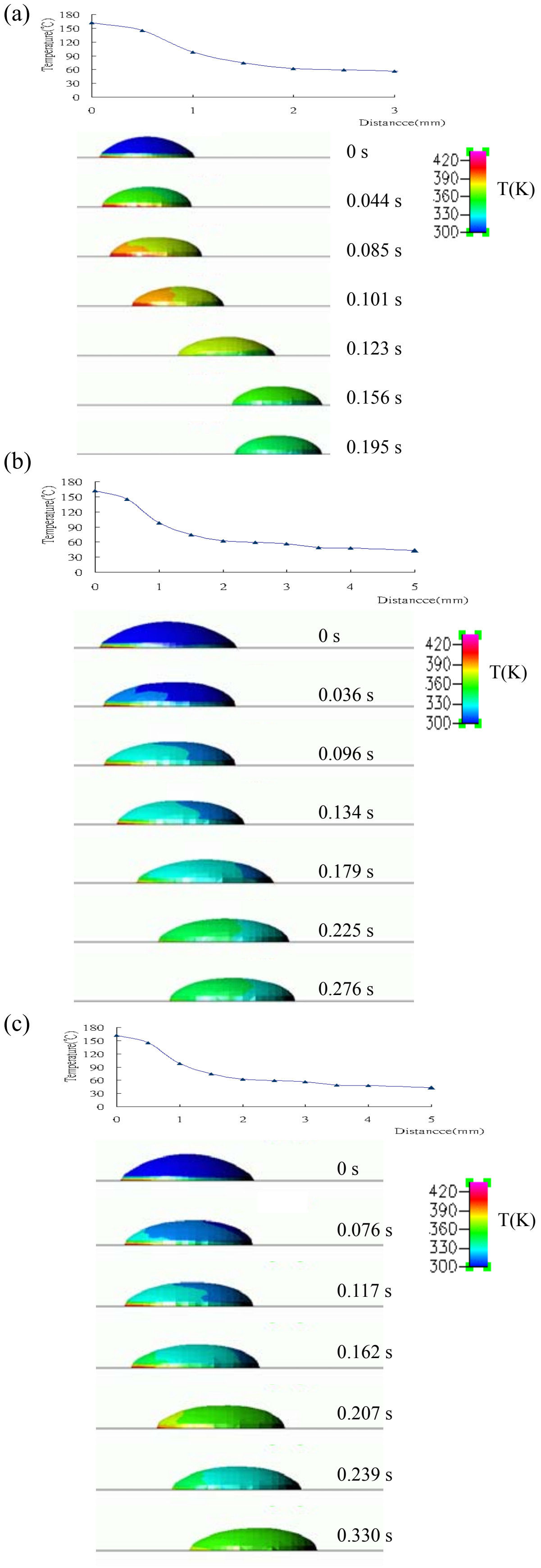

Fig 5. Computed displacement histories of the Droplets of (a) 0.1μℓ *on 1mmx2mm*, (b) 1μℓ *on 1mmx2mm*, (c) 1μℓ *on 1mmx2mm*.

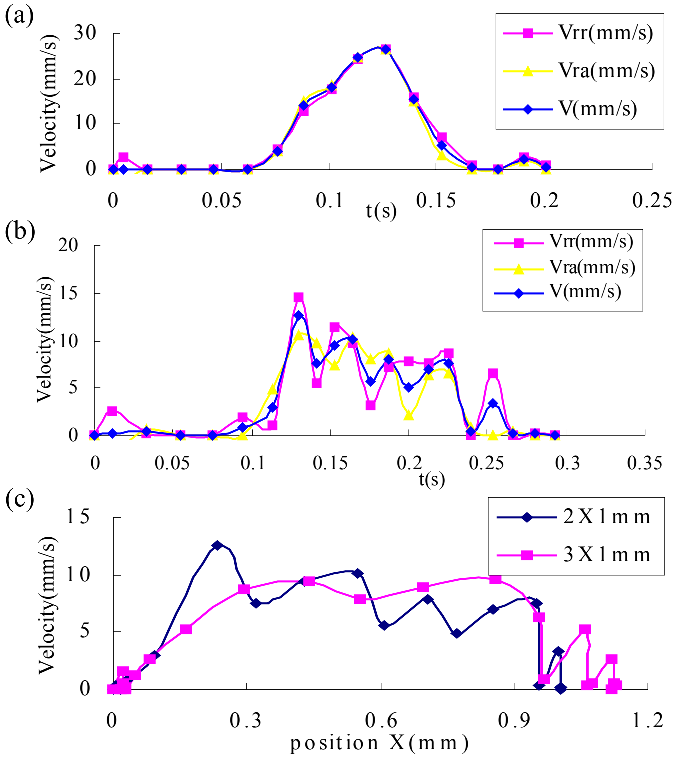

Fig 6. Compared velocity histories for microdroplet movements (a) 0.1μℓ on 2X1mm heater (b) 1μℓ on 2X1mm heater (c) 1μℓ on 2X1mm and 3X1mm heater

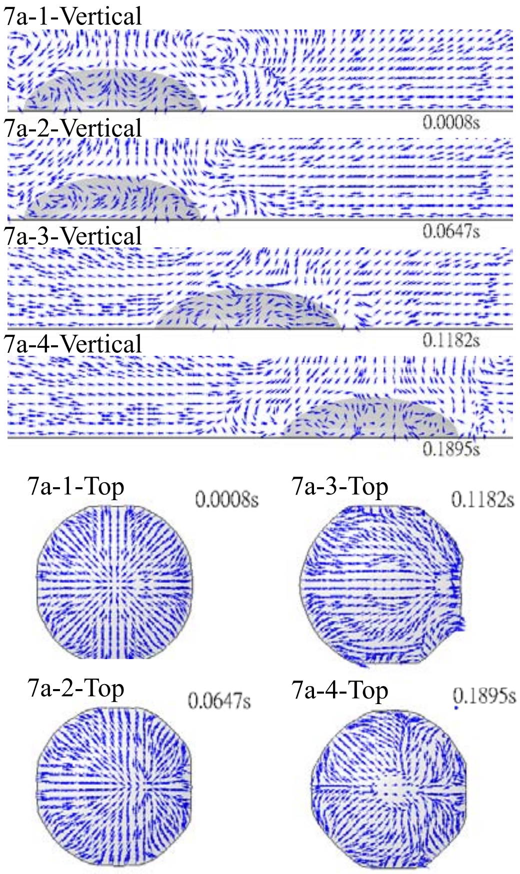

Fig 7a Velocity vectors of 0.1μℓ droplet on 2X1mm heater

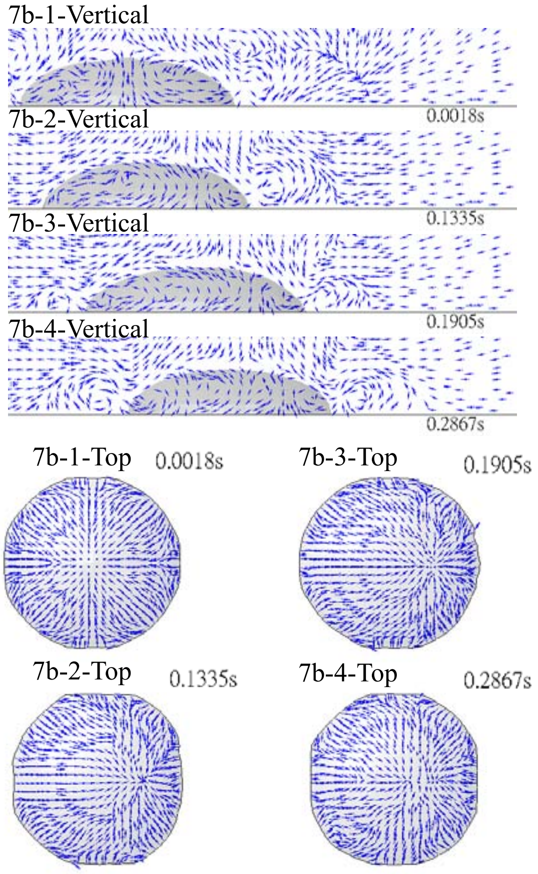

Fig 7b Velocity vectors of 1μℓ droplet on 2X1mm heater

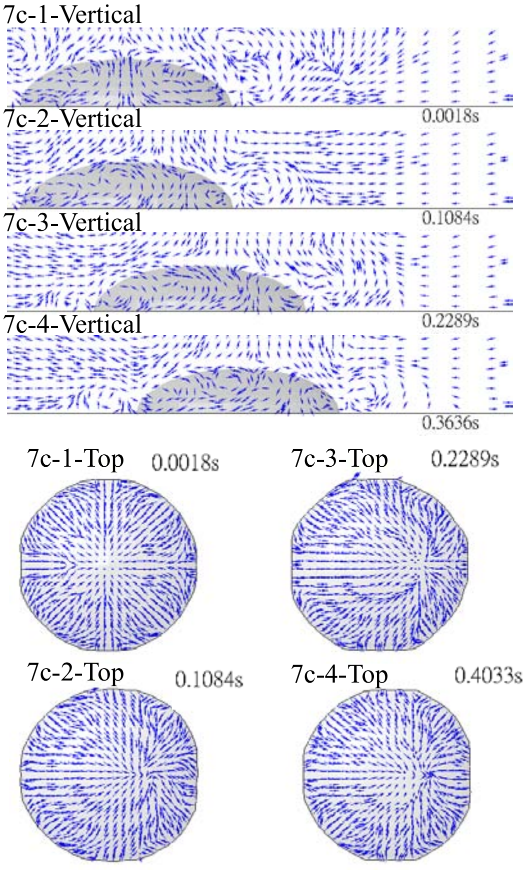

Fig 7c Velocity vectors of 1μℓ droplet on 3X1mm heater