Free Fall Mechanism of Micro Liquid Droplet

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It is important to analyze a behavior of micro liquid droplet in order to achieve a high accuracy of LSI fabrication process such as the cleaning process, the lithography process and the etching process, patterning process and so on. By using a high-speed camera, free fall behavior of a droplet is observed. The Laplace force before falling acts to a droplet effectively. By observing the position of droplet head and tail, it is observed that the micro droplet falls faster than the free fall velocity. By employing a droplet spring vibration system, the fall nature can be clarified.

Keywords: Micro droplet, Laplace, free fall, ink jet, surface tension

1. Introduction

Recently, wetting control is one important process in micro device fabrication. Particularly, micro liquid droplet control has been focused in order to achieve high precise process control such as inkjet printing and nozzle jet coating and so on. [1-4]. In this regard, we pay attention to droplet fall behavior as a basic dispense process. By using a high-speed camera, slight vibration of droplet under hanging up by meniscus neck and fall velocity faster than free fall can be confirmed. The double spring model is employed to discuss the droplet fall mechanism.

2. Experiment

A schematic of the experimental setup is shown in Fig.1a. In the experiment, as a falling water droplet, deionized water ($\gamma=72.8\text{mJ/m}^2$) was used. The nozzle diameter for droplet injection was $720\mu\text{m}$. A high-speed camera (VCC-8000, Digimo) was used for the observation of droplet falling. With the image resolution of 256×212 pixels in 1.4cm^2 area, the system can record droplet images at 1000 frames/sec. As shown in Fig.1b, the droplet head and tail positions from the nozzle apex were measured. The position of $y=0\text{mm}$ can be defined

as nozzle apex. All experiments were carried out at the ambient conditions, 20.0°C and 30%RH.

Fig.1 Experimental setup; (a) the experimental apparatus, (b) Definition of droplet position after drop from nozzle apex.

Fig.2 Sequential images of droplet falling. The time t_1 is defined as a moment at droplet separation from nozzle apex.

3. Results and Discussion

We can obtain the observation results of droplet falling as shown in Fig.2. The time $t_1=0$ s can be defined as the separation moment from a nozzle apex. The images of free droplet until separation (I) and droplet falling behavior (II) are recorded for every 5ms by using the high speed camera. The droplet diameter was 3.06mm at $t_1=0$ s. The droplet is hung by the slight water meniscus. Figure 3 shows the droplet positions, head and tail, as time passage. The symbols y_1 and y_2 are defined as droplet tail and head positions as shown Fig.1b. Before falling (I), the droplet position increases gradually, which means the tension of water meniscus. The Laplace force acting on the water

Fig.3 The Droplet positions at head and tail as the passage time.

meniscus is defined as the following equation.[6]

$$F = \pi R_0^2 \gamma \sin^2 \alpha \left(\frac{1}{R_1} - \frac{1}{R_2} \right) + 2\pi R_0 \gamma \sin \alpha \sin(\alpha + \theta) \quad (1)$$

where symbols F , γ and R_0 represent Laplace force, surface energy and radius of droplet as shown in Fig.4. The symbols θ and α represent the contact angle of the meniscus and the center angle of droplet. The radius R_1 and R_2 indicate the curvature radius of meniscus. In Fig.4a, the following values are obtained, $R_0 = 1.5$ mm, $R_1 = 1.0$ mm, $R_2 = 0.85$ mm, $\alpha = 5^\circ$, $\theta = 27.8^\circ$. The Laplace force F acting on water droplet is estimated to be 0.086mN.

We focus on the droplet fall region II in Fig.3. The droplet head and tail positions are plotted in

Fig.4 Analysis model of Laplace force based on meniscus shape of water droplet.

Fig.5. The data indicate the center position of the droplet. We attempted to analyze the free fall behavior of droplet without air resistance. The symbols of y_g and y_{g0} are defined as the positions of droplet in free falling and initial position of droplet at $t_1=0$ s. The following motion equation can be defined.

$$y_g - y_{g0} = \frac{1}{2} g t_1^2 \quad (2)$$

where the symbol g represents acceleration due to gravity. The free fall behavior is shown in Fig.5a as a solid curve. It is clearly observed that the experimental data of water droplet falling is different from the theoretical free fall nature. The water droplet falls faster than that under free fall. In this regard, an initial velocity v_0 at $t_1=0$ of the droplet is employed as the following equation.

$$y_g - y_{g0} = \frac{1}{2} g t_1^2 + v_0 t_1 \quad (3)$$

By the fitting with experimental data, the initial velocity can be estimated to be 0.07 m/s.

Then, we focus on the droplet nature in more detail. Figure 6 shows the variation of the falling droplet diameter observed in Fig.2. It is observed clearly that the water droplet vibrates slightly and changes its size during fall. Based on the observation data, assuming that variation of the droplet diameter is simple harmonic motion. Therefore, the following formula can be considered.

$$x = A_v \sin(\omega t_1 + \phi_0) + x_0 \quad (4)$$

where symbol x is droplet diameter, A_v is amplitude parameter, ω is angular frequency, t_1 is time, ϕ_0 and x_0 are initial phase and position. By the fitting with experimental data, the ω value is obtained as 448.7 rad/s. Hence, the spring constant of a droplet can be estimated. The ω in Eq.4 at simple harmonic motion is defined as follows.

$$\omega_2 = \sqrt{\frac{k_2}{m_2}} \quad (5)$$

where symbols ω_2 and k_2 represent the angular frequency and spring constant of the water droplet. Volume of the droplet calculated as 1.5ml from the photograph. Density of water was 998.2 kgm^{-3} at

(a) Droplet position at passage time.

(b) Droplet position and passage time (logarithm).

Fig.5 Difference of water droplet falling from free fall motion.

Fig.6 Vibration of droplet size during falling.

Fig.7 Schematic illustration of double spring model composed with meniscus and droplet.

20.0°C. Consequentially, the spring constant k_2 of water droplet can be determined to be 2.83N/m. In order analyze the falling nature of water droplet, it is employed that the double spring vibrating system as shown Fig.7. The water meniscus and droplet are regarded as certain springs. The equation of motion of this model can be expressed based on the force balance as follows.

$$\begin{cases} m_1 \frac{d^2 y_1}{dt^2} + k_2 (y_1 - y_2) + k_1 (y_1 - Y \sin(\omega t)) = 0 \\ m_2 \frac{d^2 y_2}{dt^2} - k_2 (y_2 - y_1) = 0 \end{cases} \quad (6)$$

Fig.8 Dependency of position and time.

Solving the above equation.

$$\begin{cases} y_1 = \frac{(-\omega^2 + \omega_{12}^2)\omega_{11}^2 Y \sin \omega t}{\omega^4 - \omega^2(\omega_{11}^2 + \omega_{12}^2 + \omega_{21}^2) + \omega_{11}^2 \omega_{12}^2} \\ y_2 = \frac{\omega_{11}^2 \omega_{12}^2 Y \sin \omega t}{\omega^4 - \omega^2(\omega_{11}^2 + \omega_{12}^2 + \omega_{21}^2) + \omega_{11}^2 \omega_{12}^2} \end{cases} \quad (7)$$

where $\omega_{11} = \sqrt{k_1/m_1}$, $\omega_{12} = \sqrt{k_1/m_2}$, $\omega_{22} = \sqrt{k_2/m_2}$. The meniscus spring constant k_1 is obtained based on Hooke's law with the volume of the meniscus bridge, 0.2 μl , from the observed image and the Laplace force 0.086mN from Eq.1. Based on Eq.7, the vibrating motion of water droplet and meniscus are shown in Fig.8. The vibration frequency of water droplet is determined as 71.4Hz from Fig.6. In Fig.8, the positions of water meniscus y_1 and droplet y_2 are estimated at the two representative frequency 80 and 64 Hz. In the initial stage less than 6ms in 80Hz and 8ms in 64Hz, the downward force F_2 acts to water droplet. The same mode of vibration is repeated periodically. It can be considered that the water droplet should be separated in this mode. Moreover, the downward force is added to the falling droplet. This is the reason of that the water droplet falls faster than free fall one as shown in Fig.5.

4. Conclusion

We critically analyzed the behavior of micro water droplet by the high speed camera measurements. The mechanism of droplet falling is explained by employing the double spring model. The obtained results in this paper can be applied to various industrial processes controlling the micro liquid drops.

References

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