3P1-1

Direct Observation of Microdroplets Penetrating Porous Substrate
微小液滴の多孔質基板への浸透過程直接観察

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1. Introduction

In recent years, inkjet technology is applied to various industrial fields, such as printing and 3D fabrication of mico-structures. In those applications, it is important to observe the behavior of micro-liquid droplets on the solid substrate after they fly in the air and reach the substrate. The radius of droplet commonly used is less than 50 μm and typical time scale of dynamics of the microdroplet is 1~100 μs, therefore it has been difficult to observe the droplets directly even if we use a high speed camera.

Upto now, large droplets as large as 1 mm in diameter were used in study of interaction between droplets and substrates[1-2]. In this conventional observation, however, the expected time scale required for the stable and equillibrium state is in the order of second for such larger droplets: larger droplets require longer time. Unfortunately, time scale of molecular dynaics, such as adsorption of surfactants on to the surface is in the order of μs. To undertand the dynamics of the inkjet droplets on hard substrates, we should observe the inkjet droplets with much higher time resolution.

In our previous research[3], we observed flying droplets using stroboscopic technique with high time resolution less than 1 μs. In this work, we developed new observation system of microdroplet dynamics on the substrate with stroboscopic method.

2. Experiment

The schematic image of our experimental system in this work is shown in **Fig. 1**. The key feature of this system is an operation technique of the motorized stage to constantly provide fresh surface of the substrate. The stage is built up with a combination of liner and rotary ones and controlled so that the landing spot of the droplets moves in a spiral track. This technique requires only a simple operation of each stage such as movement in a fixed direction at constant speed. Nevertheless, the observation time in an experiment can be extended for over 30 minutes.

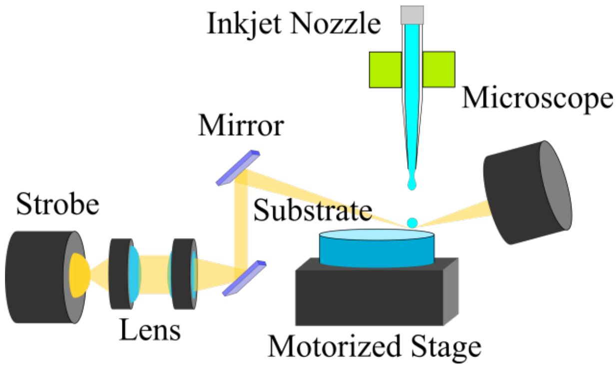

Fig. 1 Schematic view of experimental setup. For strong lighting, the strobe light was focused and irradiated to the droplets.

The micro droplets were produced using drop-on-demand system, as described in our previous work[4]. We generated droplets with the diameter of approximately 30 μm at speeds of 1~2 m/s at 5 Hz.

For the first demonstration of the performance of this system, we employed porous glasses as the substrate, which is expected to show rapid absorption of the touching liquid. The samples were purchased from Akagawa Glass, whose pore size are 4 nm and 50 nm (**Table 1**). As the sample liquid, distilled water and ethylene glycol were used.

3. Result and discussion

The pictures of the penetration on the porous glass are shown in **Fig. 2**. While the droplet spread until about 30 μs, droplet width w hardly changed

Table 1 Specifications of the porous glasses.

Pore size [nm]	**Specific gravity**	**Porosity [%]**	**Internal surface area [m^2/g]**
4	1.57	28.6	200
50	1.12	49.1	80

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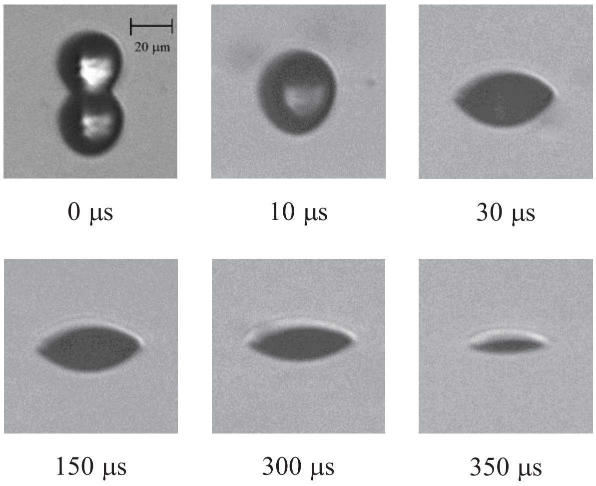

Fig. 2 Water droplets penetrate into a porous glass with pore size 50 nm. The lower half of droplets are images of the droplets reflected on the substrate.

and contact angle decreased gradually after 30 µs. At about 300 µs, contact angle was equal to the receding contact angle, and then the width decreased. Finally, the droplet penetrated perfectly by 400 µs. This time scale changed by the combination of a liquid and a substrate. The combination of ethylene glycol and 4 nm porous glass had the largest time scale.

For convenience of analysis, the images of the droplets were binarized, and the width and height of the droplet were measured. From these two parameters, the contact angle and the volume can be calculated, and the temporal changes of the combination of water and 50 nm porous substrate are shown in **Fig. 3** and **Fig. 4**.

Here, we can discuss the dynamics of penetration of droplets by volume change of the droplets. The penetration behavior can be described by Lucas-Washburn equation[5] (LW equation). This equation indicates that porous glasses or papers have tremendous capillaries and liquid penetrates into the substrate by capillary force. The volume of penetrated liquid is written as the following equation under the condition that the contact area is constant.

$$V_p(t) = p^{\frac{2}{3}} S \sqrt{\frac{r\gamma \cos\theta}{2 \ \eta} t} \qquad (1)$$

where p, S, r, γ, θ and η are the porosity, the contact area, the pore size, the surface tension, the contact angle and the viscosity, respectively.

The solid line shown in Fig. 4 represents a fitted curve of eq. (1) to the experimental data. Using the constant values of S and θ obtained from the image analysis above mentioned, the data were well fitted over wide range. We also found that the other combinations of liquids and substrates yielded to LW equation.

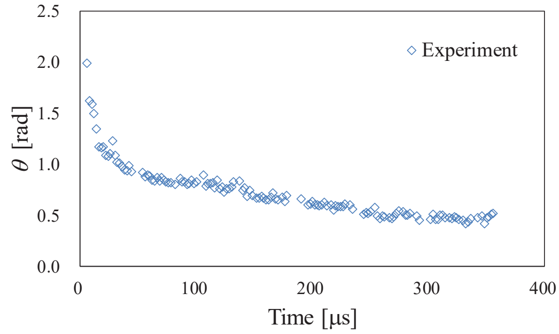

Fig. 3 Contact angle versus time.

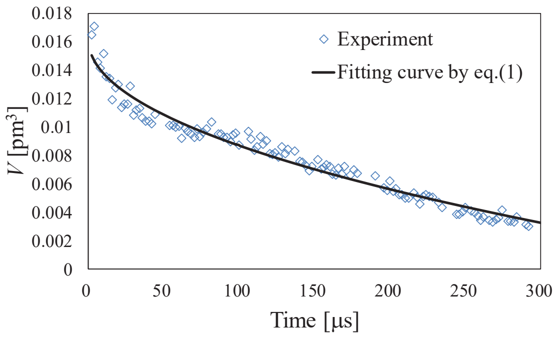

Fig. 4 Droplet volume versus time. The solid line is the fitting curve by eq. (1).

4. Conclusion

The penetration dynamics of microdroplets on the porous glass were investigated. Observing the droplet dynamic behavior directly, we analyzed wetting and penetration of droplets on the porous substrates with less than micro second time resolution. The result indicates that penetration of pico-liter inkjet droplets also follows the Lucas-Washburn equation.

Acknowledgment

This work was partially supported by a Sentan program from Japan Science and Technology Agency, JST.

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