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DEVELOPMENT OF A REPEATABLE SINGLE-DROPLET GENERATOR USING A STEP MOTOR AND PWM CONTROL OF A TWO-WAY SOLENOID VALVE

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ABSTRACT

A device capable of repeatedly generating a single droplet was developed. A piston pushes the liquid into a cylinder, creating droplets that are emitted from the nozzle outlet. A one-dimensional linear stage connected to a stepper motor was used for piston displacement. To repeat the generation of single droplets, a method that consists of generating droplets, supplying liquid into the cylinder, and blocking the inflow of external air through the nozzle outlet during the process of supplying liquid into the cylinder was developed. To prevent the inflow of external air into the cylinder through the nozzle outlet, a two-way solenoid valve was installed in the supply passage between the cylinder and the reservoir holding the liquid supply. The sudden opening of the two-way solenoid valve is prevented by PWM (pulse width modulation) control of the current supplied to the solenoid, and the air inflow into the cylinder through the nozzle outlet can be successfully blocked by this method. PWM control of the driving current in the solenoid enabled the repeated generation of single droplets. A single-droplet-generation experiment was repeatedly conducted while varying the nozzle diameter and the hydraulic head difference Δh between the nozzle outlet and the liquid reservoir. The ratio of the droplet diameter to the nozzle diameter was 5.45 with a nozzle diameter of 0.23 mm and convergence to 2.1 with an increase in the nozzle diameter to 1.51 mm. When repeated measurements were taken under fixed experimental conditions, the droplet diameter deviation % (=stdev/average*100) showed a distribution of 1 ~ 6%.

Keywords: single droplet generation, repeatable droplet generation, pulse width modulation, step motor, two-way solenoid valve.

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INTRODUCTION

A droplet generator is a device that generates droplets of the same size at a desired frequency. The droplet generator is mainly used as a device to study the droplet breakup, impingement, evaporation, and combustion characteristics in combustors that use liquid types of fuel, such as internal combustion engines and rockets. Droplet generators are also being used in studies related to aerosol behavior to understand air pollution mechanisms. As a clean room for semiconductor production requires highly precise maintenance and management of cleanliness, it is necessary to measure the degree of contamination in such rooms accurately. Therefore, a device capable of generating droplets of the same size is required for the calibration of standard measuring equipment to measure the degree of contamination in a clean room.

Droplet-generation methods can be classified into three types: dripping, continuous generation, and drop-on-demand types [1]. The dripping method generates droplets through interaction between gravity and the surface tension acting on droplets suspended from the tip of the nozzle, and the droplet generation frequency is low. The dripping method is used to measure the surface tension and contact angle of the liquid [1]. The continuous-droplet-generation method generates droplets of the same size at a constant frequency by applying pressure to a liquid. This method has a high droplet velocity and high generation frequency. Thus, continuous droplet generation has been used in research on droplet breakup mechanisms in a high-speed airflow [2, 3], the deformation and breakup characteristics of droplets when they collide with a wall [4], droplet collisions and coalescence [5, 6] and ink-jet printing, among others. The DOD method generates droplets by applying pressure to a liquid for a certain period using a device such as a piezoelectric element. The DOD method can generate a droplet of a certain volume or a single droplet at a desired time. The DOD droplet-generation method can supply droplets in the range of 1 μm to 100 μm at a desired amount and timing [7-9]. The DOD droplet-generation method is mainly used for ink-jet printing [10-12]. The single-droplet-generation technology by DOD can be used to study wall collisions of droplets and the evaporation and combustion characteristics of droplets. Also, the DOD method can be used for precise control of the supply of a reagent, such as for automatic titration [13].

To study the breakup, coalesce, collision, evaporation, and combustion of droplets in a combustor, a device capable of generating a single droplet is required. Several researchers have conducted studies of droplet generators capable of generating single droplets. Schneider and Hendricks [14] and Schneider et al. [15] generated droplets by vibrating a capillary tube with a piezoelectric transducer. A single droplet could be generated by deflecting the generated droplets electrostatically under the charging conditions used in their work. Harris et al. [16] developed a system that generates a single droplet by vibrating a low-cost piezo-buzzer. Sadeghian et al. [17] also generated droplets by deforming the piezo-buzzer; the size

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and speed of the droplets could be varied according to the magnitude of the voltage applied to the piezo-buzzer.

Droplet generators using a piezoelectric element are highly sensitive to the magnitude of the voltage applied to the piezoelectric element, and precise tuning is required to generate droplets of the same size repeatedly. Albadi and Zhang [18] developed a simple system that generates a single droplet by controlling the pressure of the liquid supplied to the nozzle without using a piezoelectric element. In this system, droplets are generated from a nozzle due to the installation of an opening/closing valve between the nozzle and the liquid accumulator. The size and initial velocity of a single droplet change according to the pressure generated by the liquid accumulator and the valve actuating time. The droplet size fluctuation rate is 5-10%.

In this study, we developed a new, repeatable single-droplet generator that mitigates the disadvantages of the piezo type and Albadi and Zhang's single-droplet generator. The droplet generator here consists of a piston, a cylinder, and a two-way solenoid valve controlled by a PWM signal. When the piston moves downward in the cylinder, a single droplet is created, and when the piston moves upward to return to its original position, the liquid is supplied from the reservoir into the cylinder. A two-way solenoid valve exists in the liquid supply line between the reservoir and the cylinder, and an optimal control method was developed to generate a single droplet.

EXPERIMENTS

Figure-1 shows a schematic diagram of the experimental setup. Droplet generation is achieved by pushing the liquid against a piston with a diameter of 50 mm moving vertically downward. The up-and-down movement of the piston is achieved by a 1-D linear stage driven by a step motor. Step motor control is realized by a PC and a DAQ board (NI-USB 60. 08). The liquid supply device was designed to maintain a liquid hydraulic head difference of Δh between the nozzle outlet and reservoir 2 at a constant value.

The liquid supply system consists of reservoir 1, reservoir 2, an overflow tank, and a peristaltic pump. To maintain Δh constantly, the liquid level in reservoir 2 must be constant. To this end, when the liquid level in reservoir 2 exceeds a certain value, the liquid overflows. The overflowing liquid is continuously sent to reservoir 1 by the peristaltic pump. The liquid in Reservoir 1 falls back to Reservoir 2 at regular intervals to keep the liquid level in Reservoir 2 constant. Meanwhile, the liquid in reservoir 2 passes through the two-way solenoid valve and then through the hole on the upper surface of the drop generator piston and is supplied to the inside of the cylinder.

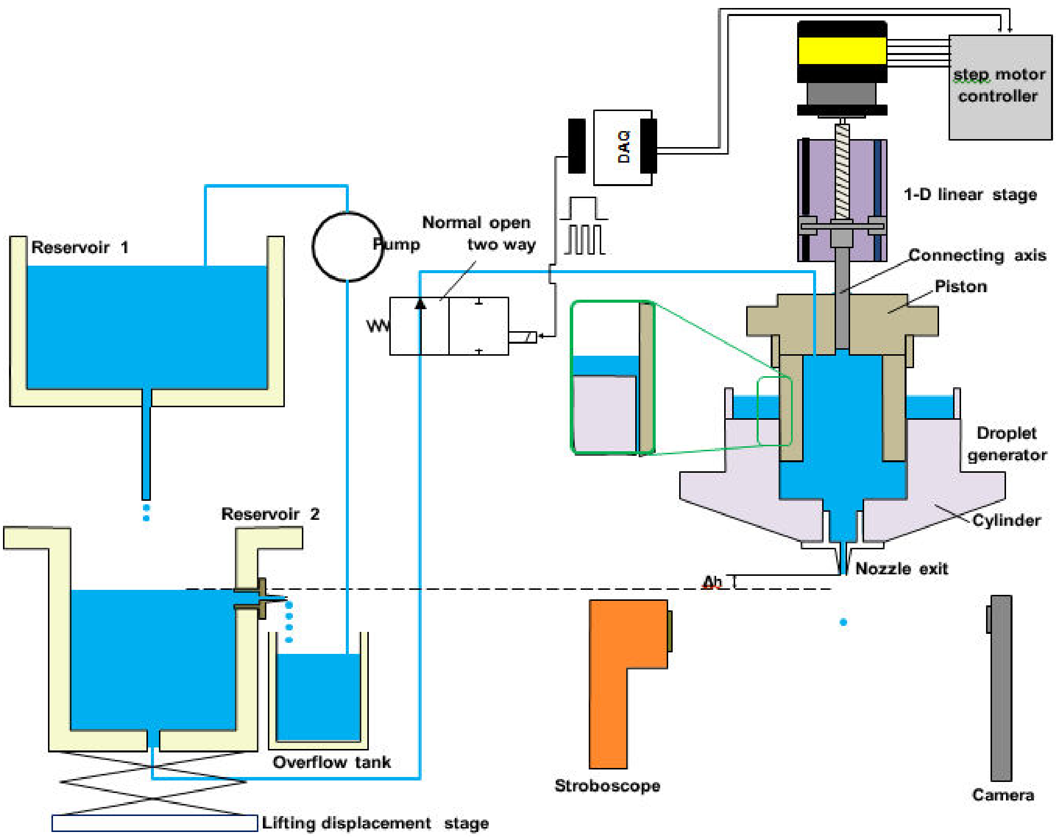

Figure-1. Experimental setup of the repeatable single-droplet generator.

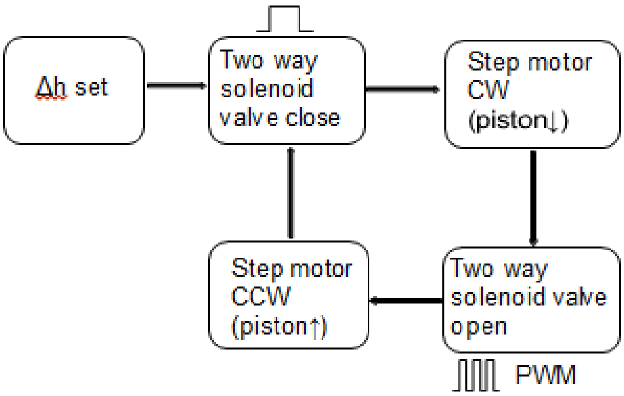

Figure-2. Control algorithm of the two-way solenoid valve for generating a single droplet repeatedly.

The two-way solenoid valve closes when the piston moves downward to generate droplets and opens when the piston moves upward so that the liquid in reservoir 2 is supplied to the inside of the cylinder. There is a gap of 0.1mm between the cylinder and the piston to ensure that the piston moves smoothly. To seal the gap, liquid is supplied to the upper part of the cylinder and maintained at a certain height. Figure-2 summarizes the device control algorithm for repeatedly generating single droplets as described above.

Figure-3 shows the relationship between the number of pulses that must be input to the stepper motor controller and the nozzle diameter to generate a single droplet. When the number of input pulses is 120, the distance the piston moves in the vertical direction is 1 mm. As the nozzle diameter increases, the number of input pulses to the step motor controller for single-droplet generation tends to decrease. This occurs because the resistance to the liquid flow within the nozzle decreases as the nozzle diameter increases. When the nozzle diameter was 0.23 mm, the number of input pulses was 32, when the nozzle diameter was 0.56 mm, the number of input pulses decreased rapidly to 4; at 1.17 mm or more, the number of pulses converged to 2.

Confirmation of single-droplet generation and measurement of the droplet diameter was done using visualization. A stroboscope was used as a visualization light source. For high-speed shooting, the smartphone's

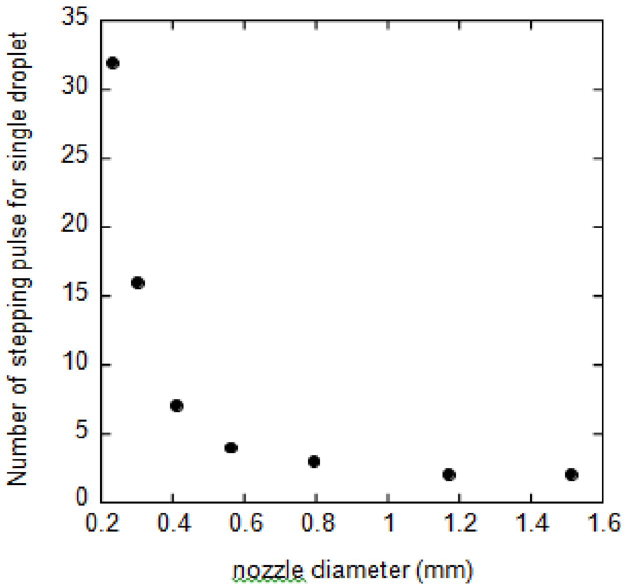

Figure-3. Number of stepping pulses for a single droplet according to the nozzle diameter.

A high-speed shooting function was used. Given that the flash rate of the stroboscope was set to 60 Hz, the smartphone filmed at 60 frames/sec. As shown in Figure-1, a forward-scattering image of a droplet illuminated by the stroboscope flashlight was taken with the camera. When combining Δh and the nozzle diameter, for each single-droplet-generation step, visualization was repeated 20 times. Δh was set in 11 cases at 1 mm intervals in the range of -10 mm to 0 mm. In total, seven nozzles were used with different diameters of 0.23, 0.3, 0.41, 0.56, 0.79, 1.17, and 1.51 mm. Therefore, a total of 77 experimental conditions were measured. In this study, water was used as the liquid used to generate the droplets.

RESULTS AND DISCUSSIONS

The detailed control process for single-droplet generation can be summarized as follows. In the first step, Δh is adjusted by the lifting displacement stage, as shown in Figure-1. The second step closes the two-way solenoid valve to keep the liquid in the cylinder sealed. During the third step, the step motor is rotated clockwise to control the piston and have it move downward. The period of the input pulse for step motor control is 2 ms, and the number of inputs.

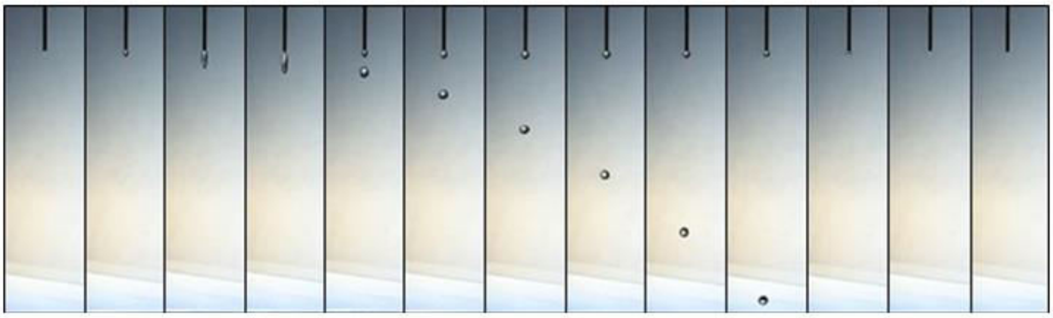

Figure-4. Consecutive captured images of a generated droplet at intervals of 1/60 second.

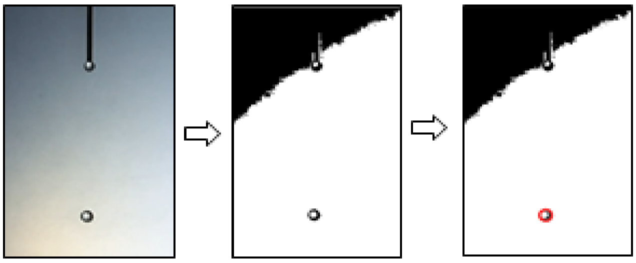

Figure-5. Image-processing steps to determine the diameter of a generated droplet: (a) original captured image, (b) a black and white image converted from the original image, and (c) detection of the diameter of a circle.

Pulses for generating single droplets according to the nozzle diameter are shown in Figure-3. As the liquid in the cylinder is pressurized, a single droplet is emitted from the tip of the nozzle. After generating a single droplet, the two-way solenoid valve opens to supply the liquid into the cylinder. At this time, if air flows into the cylinder through the nozzle outlet, repeated single-droplet generation is impossible. Therefore, the open control of the two-way solenoid valve by PWM was used for the air inflow into the cylinder as the fourth step. That is, the current supplied to the solenoid was appropriately controlled to open the solenoid valve smoothly through PWM control. The PWM control duration is 250 ms. The period and duty ratio of the PWM control pulse were set to 50ms and 50%, respectively. By controlling the current supplied to the solenoid, it becomes possible to block the inflow of air into the cylinder through the nozzle outlet successfully during the opening of the two-way solenoid valve. In the fifth step, the two-way solenoid valve was kept fully open for 50 ms. In the sixth step, the step motor is rotated counterclockwise so that the piston moves upward and returns to its initial position. The period and duty ratio of the control pulse input to the step

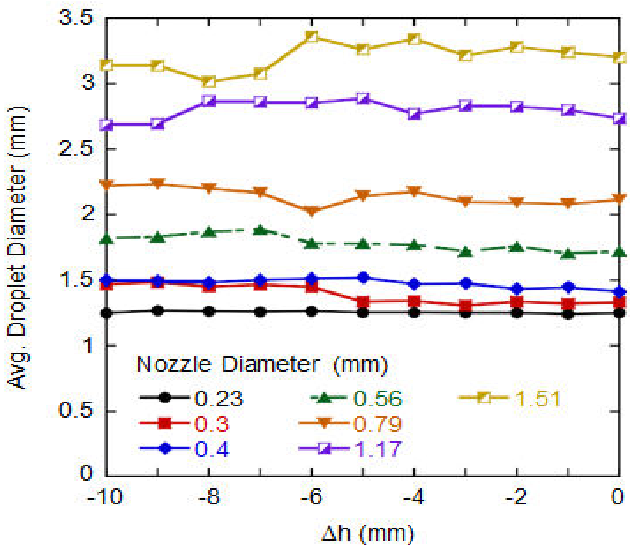

Figure-6. Average droplet diameter according to the hydraulic height difference Δh.

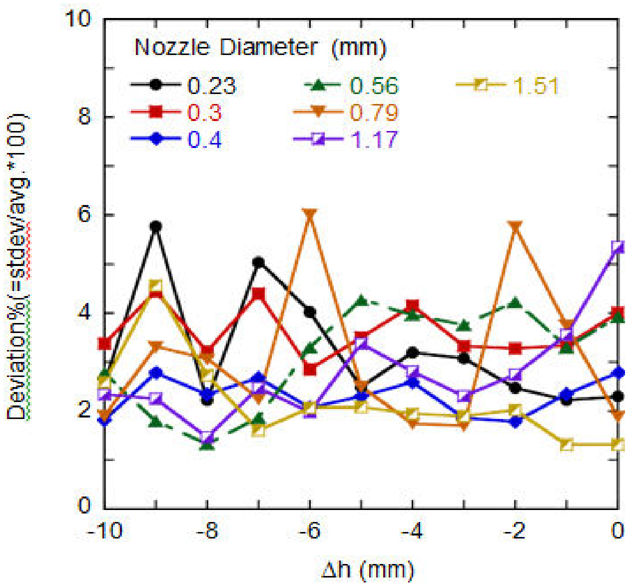

Figure-7. Droplet diameter deviation % according to the hydraulic height difference Δh.

Motor for the counterclockwise rotation are 100 ms and 50%, respectively, and the number of pulses is made to be identical to those in the clockwise rotation. In the sixth step, because the two-way solenoid valve is open, the liquid in reservoir 2 is naturally supplied to the cylinder. Subsequently, the open state of the two-way solenoid valve is maintained for 1.5 seconds. By repeating steps 2 to 6 above, the desired number of single droplets can be generated.

Figure-4 shows consecutive captured images taken during the single-droplet-generation process under the conditions of a Δh value of 6 mm and nozzle diameter of 0.56 mm. It is not possible strictly to match the step-by-step images in Figures 4(a)-4(m) with each step of the six-step

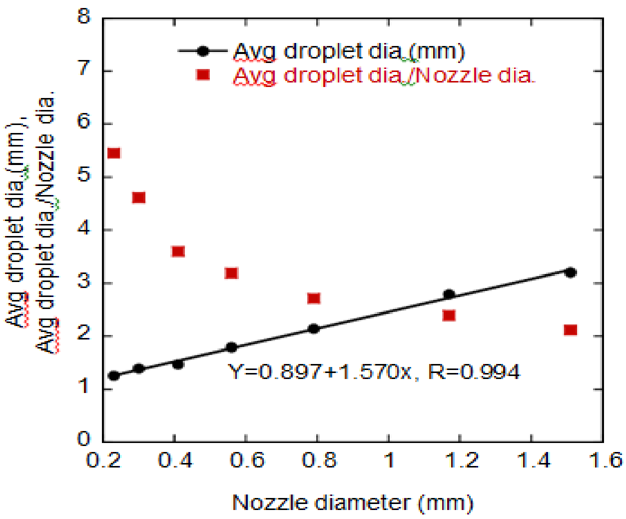

Figure-8. Average droplet diameter and ratio of the average droplet diameter to the nozzle diameter according to the hydraulic height difference Δh.

The control method for single-droplet generation was described in detail earlier, but a rough distinction is as follows. Figure- 4(a)-Figure-4(d) are images of the step during which the pushing of the droplet to the nozzle outlet is done when the piston moves downward upon the clockwise rotation of the step motor. Figure-4(e) is an image in which a single droplet is generated. Figure-4(e)-Figure-4(m) depicts the control steps used to block the inflow of air into the cylinder through the nozzle outlet by PWM, which controls the two-way solenoid valve. The frame image in the subsequent control step is omitted in Figure-4, and the same image frame shown in Figure-4(m) without a droplet is continued. The droplet-generation experiment was repeated 20 times under one experimental condition in which the nozzle diameter and Δh were combined.

Figure-5 shows the image processing steps used to determine the droplet diameter by extracting the captured image. For single-droplet generation, the image was taken at 60 frames per second while the droplet-generation process from step 2 to step 6 was repeated 20 times, with the images captured continuously. The total number of frames during 20 repeated instances of single-droplet generation is approximately 2400-6000, varying according to the number of input pulses for control of the step motor. Among the total frames captured for each experimental condition, only the frames in which the droplet was separated from the nozzle outlet were extracted, and the frames corresponding to this are shown in Figure-4(e)~Figure-4(j). Among the extracted frames, only that shown in Figure-4(j) underwent image processing to determine the droplet diameter. All image-processing steps were done using Matlab functions. First, Figure-5(a) was converted into a black-and-white image; this result is shown in Figure-5(b). Using Matlab's imfindcircles function, circles were detected from the image in Figure-5(b). The result of detecting the circles is shown in Figure-5(c). The droplet diameter was obtained from the results in Figure-5(c).

The diameter of a single droplet using the aforementioned image-processing method was determined in each experimental condition and set as a combination of seven cases of nozzle diameters and 11 cases of Δh. The average droplet diameter obtained with this method is shown in Figure-6. When Δh was changed for one nozzle diameter, the average diameter remained similar. Figure-7 shows the deviation % (=stdev/avg*100) of the droplet diameter obtained when repeating the process 20 times under identical experimental conditions. The droplet diameter deviation % ranged from 1 to 6%. When the nozzle diameters were 0.79 mm and 0.23 mm, the deviation % variation exceeded that of the other nozzle diameters. It is necessary experimentally to determine the optimum Δh that minimizes the % deviation when repeating the droplet-generation process. In this experiment, when Δh is -8 mm, the deviation % for all nozzle diameters shows a minimum value with a distribution of 1 to 3%.

Figure-8 shows the change in the average droplet diameter according to the nozzle diameter. The average droplet diameter for a given nozzle was obtained by averaging all generated droplet diameters while varying Δh. The average droplet diameter tends to be linearly proportional to the nozzle diameter. The linear relationship between the average droplet diameter and the nozzle diameter is shown in Figure-8. The correlation coefficient of the linear relationship is 0.994. The average droplet diameter divided by the nozzle diameter (ADD (average droplet diameter)/ND (nozzle diameter) ratio) is represented by the solid square symbol. The ADD/ND ratio value is 5.45 when the nozzle diameter is 0.23 mm, converging to nearly 2 when the nozzle diameter is 1.51 mm. The ADD/ND ratio value of 2.1 at a nozzle diameter of 1.51 is very close to the value of 1.89 for the Rayleigh breakup mechanism of a falling liquid jet [19].

CONCLUSIONS

To repeat the single-droplet generation, methods that controlled the generation of the droplet and the liquid supply to the cylinder were devised, as was a control method for blocking the inflow of external air into the cylinder through the nozzle outlet during the process of supplying liquid to the cylinder, thus facilitating the following conclusions.

By installing a two-way solenoid valve in the supply passage between the cylinder and the liquid supply reservoir and controlling the current supplied to the solenoid using PWM (pulse width modulation), it was possible to block the air inflow into the cylinder through the nozzle outlet. Blocking the air inflow into the cylinder through the nozzle outlet allowed us to generate single droplets repeatedly.

The ratio of the average droplet diameter to the nozzle diameter was 5.45 when the nozzle diameter was 0.23mm, and it decreased as the nozzle diameter was increased, reaching 2.1 when the nozzle diameter was 1.51mm, a value nearly identical to that associated with the Rayleigh breakup mechanism of a falling liquid jet.

When the generation of a single droplet was repeated under the condition in which the nozzle diameter and Δh were fixed, the deviation % (=stdev/average*100) of the droplet diameter showed a distribution of 1 to 6%, and with the optimal value of Δh, it showed a distribution of 1~3% at all nozzle diameters.

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REFERENCES

[1] H. Dong, W. W. Carr, and J. F. Morris. 2006. An experimental study of drop-on-demand drop formation. PHYSICS OF FLUIDS. 18, 072102.

[2] Z. Liu and R. D. Reitz. 1997. An analysis of the distortion and breakup mechanisms of high-speed liquid drops. International Journal of Multiphase Flow. 23: 631-650.

[3] C. H. Lee and R. D. Reitz. 2000. An experimental study of the effect of gas density on the distortion and breakup mechanism of drops in high-speed gas stream, International Journal of Multiphase Flow. 26: 229-244.

[4] C. Mundo, M. Sommerfeld and C. Tropea. 1995. Droplet-wall collisions: experimental studies, International Journal of Multiphase Flow. 21: 151-173.

[5] M. Orme. 1997. Experiments on droplet collisions, bounce, coalescence and disruption, Prog, Energy Combust. Sci. 23: 65-79.

[6] Y. J. Jiang, A. Umemura and C. K. Law. 1990. An experimental investigation on the collision behavior of hydrocarbon droplets. Journal of Fluid Mechanics. 234: 171-190.

[7] P. Calvert. 2001. Inkjet printing for materials and devices, Chem. Mater. 13: 3299-3305.

[8] T. Creagh and M. McDonald. 2003. Design and performance of inkjet print heads for non-graphic-arts applications, MRS Bulletin. 28: 807-811.

[9] B. J. de Gans, P. C. Duineveld, and U. S. Schubert. 2004. Inkjet printing of polymers: State of the art and future developments, Advanced Materials. 16: 203-213.

[10] Q. Xu and O. A. Basarana. 2007. Computational analysis of drop-on-demand drop formation, Physics of Fluids, 19 102111.

[11] S. I. Zoltan. 1972. Pulsed droplet ejection system, U.S. Patent No. 3, 683, 212.

[12] E. L. Kyser and S. B. Sears. 1976. Method and apparatus for recording with writing fluids and drop projection means therefore, U.S. Patent No. 3, 946, 398.

[13] R. E. Lemke and G. M. Hieftje. 1982. A new directly computer-controlled pH-stat., Analytica Chimica Acta. 141, 173-186.

[14] J. M. Schneider and C. D. Hendricks. 1964. Source of Uniform-Sized Liquid Droplets. Review of Scientific Instruments. 35: 1349-1350.

[15] J. M. Schneider, N. R. Lindblad, C. D. Hendricks, and J. M. Crowley. 1967. Stability of an Electrified Liquid Jet. Journal of Applied Physics. 38: 2599-2605.

[16] D. M. Harris, T. Liu, J. W. M. Bush. 2015. A low-cost, precise piezoelectric droplet-on-demand generator. Exp. Fluids. 56-83.

[17] H. Sadeghian, Y. Hojjat, M. Ghodsi, M. R. Sheykholeslami. 2014. An approach to design and fabrication of a piezo-actuated microdroplet generator. International Journal of Advanced Manufacturing Technology. 70: 1091-1099.

[18] Albadia and Y. Zhang. 2020. A versatile droplet on demand generator based on active pressure control, Review of Scientific Instruments. 91: 125005.

[19] H. Lefebvre. 1989. Atomization and Sprays, Hemisphere Publishing Corp.