Experimental study on a solenoid valve-based generator for droplet generation

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Abstract. An on-demand droplet generator is developed based on a high-speed and 2-way solenoid valve and studied experimentally in this paper. It is found that the valve-based droplet generator has good controllability, repeatability and stability. Under a suitable applied pressure, a single droplet can be generated by opening the valve with a short voltage pulse. Besides, the droplet size can be conveniently controlled by the applied liquid pressure and pulse width of the control signal. The results show that the present device succeeds to avoid the limitation of an appropriate outlet pressure required at nozzle tip for most droplet generators in the literature and is capable of producing droplets in a wide size range for a fixed nozzle diameter.

1. Introduction

The formation of droplets is a common phenomenon in nature such as cloud droplets, and meanwhile to produce controllable droplets is required for many industrial applications including liquid crystal displays [1], drop-based manufacturing [2], inkjet printing [3], and the research on aircraft icing caused by supercooled clouds [4, 5], etc.

Droplets have been gained a scientific interest for more than one century and the development of a droplet generator which can precisely control the volume of droplets always has been focused on extensively. In the past two decades, different kinds of droplet generators have been developed in the literature by a variety of devices. For instance, the piezoelectric buzzer was generally used as an actuator to squeeze out drops when a voltage pulse is applied, for which the droplet diameter can be controlled by the voltage signal and nozzle diameter [1, 6, 7]. Another commonly used approach for droplet formation is pneumatic technique that a liquid-filled chamber with a nozzle was connected to a gas cylinder and the droplet is ejected when an appropriate pressure pulse is supplied [8, 9]. However, the obvious limitation of the above two methods is that the pressure at the nozzle tip should be maintained appropriately. If a lot of liquid droplets are required or the fluid line is too long, the pressure will be difficult to keep stable in the continuous process of droplet generation.

Shigeta et al. has developed a sample introduction system using a magnetic valve type dispenser and the droplet volume can be controlled by changing the inner diameter of the nozzle tip [10]. The liquid will only be squeezed out the nozzle when the valve is opened. Thus, the outlet pressure at the nozzle needn’t to be regulated carefully. The present droplet generator based on solenoid valve is inspired by this kind of design to avoid the limitations in most developed droplet generators and to generate
millimeter-scale droplets ranging from about 0.5 to 2.0 mm which is roughly equivalent to the diameter of freezing rain [11].

2. Experimental System and Method

A schematic diagram of the experimental setup is shown in Fig. 1. The body of the setup mainly consists of five systems: high-speed solenoid valve system, nozzle system, pulse signal control system, pressure control system and observation system. The high-speed solenoid valve from The Lee Company is a 2-way valve (INKX0511400A), which has faster response time and higher work frequency relative to the traditional solenoid valve.

![Figure 1. Schematic diagram of the experimental system.](image)

1. High-speed solenoid valve, 2. Stainless steel tube (Nozzle), 3. Integrated signal control unit, 4. Oscilloscope, 5. Air compressor, 6. Pressure regulator, 7. Pressure meter, 8. Fluid reservoir, 9. Gas supply, 10. Pressurized water, 11. LED light, 12. High-speed camera, 13. Computer.

The nozzle with a length of 12 mm was simply fabricated by stainless steel tube (1.0-mm inner diameter and 0.1-mm wall thickness) and connected to the solenoid valve through a fabricated metal holder.

The pulse signal control system consists of two parts: an integrated signal control unit and an oscilloscope. For the present device, the amplitude of pulse signal is constant of 12 V. We can control the pulse width and pulse interval to achieve droplet formation with different diameters and frequencies.

The pressure control system mainly consists of three parts: air compressor, pressure regulator and fluid reservoir. The air compressor can supply high pressure gas to the fluid reservoir so that the fluid is pressurized and the pressure can be exactly controlled by the pressure regulator.

The observation system consists of a LED light, a CCD camera (Phantom VEO710L, Vision Research, USA) and a computer. A video is recorded at 5000 frames/s with a resolution of 128 × 800 pixels and spatial size 20 μm/pixel in the process of droplet generation. After capturing the sequences of droplet formation, the droplet diameter can be calculated by the pixels of droplet from the captured image. The method to measure the droplet diameter is shown in Fig. 2. Firstly, we extract the edge data from the droplet image (Fig. 2(a)) with an edge recognition algorithm in MATLAB (Fig. 2(b)). Then, the continuous region in binary image can be filled as shown in Fig. 2(c). The droplet diameter finally can be calculated through the function of regionprops in MATLAB.
In this experimental research, the fluid is the ultra-pure water with the density 998 kg/m³, surface tension 72 mN·m and dynamic viscosity 0.001 Pa·s in room temperature. Besides, the droplets are generated at a low frequency of 10 Hz and the pulse width is ranging from 0.2 to 10 ms.

3. Results and Discussion

In the present droplet generation system, only the valve is opened and meanwhile the water is pressurized, the fluid can flow out the nozzle. Thus, the performance of the droplet generator is mostly affected by the applied pressure and the pulse width for a given nozzle.

3.1. Effect of the Applied Pressure on the Droplet Generation and Diameter

The applied pressure has a conclusive influence on the performance of the droplet generator, provided that the valve open time is longer than the response time. If the valve driven by a pulse signal with appropriate width, there is certainly a range of applied pressure named as valid applied pressure in this paper under which a single droplet can be generated.

Fig. 3 shows the image sequence of droplet formation for a 6-ms pulse width under the lower and upper limited valid applied pressure, 30 and 42 kPa, respectively. The necks start to form after 6 ms, i.e. the moment at which the valve is closed. After the valve closed, there are no additional fluid or external force to drive the jet and thus the fluid that has been excluded from the nozzle continues to be ejected under inertial forces. Since the different applied pressures lead to the inertial forces with different magnitude, there are tiny differences between the necks in the process of contraction. Under the upper limited applied pressure, the shrinkage at the nozzle lip causes a slender tail to generate a very small
satellite droplet at first, whereas the contraction away from the nozzle lip causes liquid residue to form a meniscus under the lower limit. If the applied pressure is less than 30 kPa, no droplet is generated and the liquid will be left on the tip of the nozzle until the accumulated drop drips caused by the gravity force. On the contrary, multiple droplets are formed by the main droplet breakage or satellite droplet pinch-off from the main droplet when the applied pressure is higher than 42 kPa.

Figure 4. Effect of the applied pressure on droplet diameter for 6-ms pulse width. The error bar represents the mean absolute deviation.

The differences in the magnitudes of applied pressure must cause the differences in the volume of fluid ejected from the nozzle. Fig. 4 shows the relationship between the applied pressure and droplet diameter when the valve is driven by a fixed pulse signal with width of 6 ms. though there are some fluctuations, the droplet diameter gradually enlarges with the increase of applied pressure as a whole. The adjustable range of droplet size is ranging from 1685 to 1860 μm. From the error bar, it was known that the droplet generator has consistency in droplet size once the experimental conditions is determined.

3.2. Effect of the Pulse Width on the Applied Pressure and Droplet Diameter

From subsection 3.1, it can be known that the valid applied pressure is sole for a fixed pulse width of the signal. Therefore, the range of valid applied pressure for different pulse widths should be determined before analysing the influence on the droplet diameter by the pulse width.

Fig. 5 shows the upper (blue curve) and lower (green curve) applied pressure limits as a function of pulse width, and the differences between the limits are usually less than 20 kPa. As the pulse width increases, the valid applied pressure decreases fast at first and then slow. It was also observed that the valid applied pressure with a pulse width of 200 μs is much higher than other conditions. The analysed reason may be that a higher pressure is in favour of fluid column breakup since the small volume of fluid flows through the valve in a very short time. What's more, the experimental results show that the error, both of the upper and lower limits of applied pressure, tends to reduce with the increasing pulse width and the scale of the valid applied pressure correspondingly narrows down, which indicates that the stability of liquid column breakup increases as the large droplet is generated under a lower applied pressure.

The pulse width of driving signal has an important influence on droplet diameter for most droplet generators and was evaluated for the present device. Fig. 6 shows the dependence of drop size on pulse width ranging from 0.2 to 10 ms under the corresponding lower limited applied pressure (green curve in Fig. 5). The measured results show that the droplet diameter dramatically increases when the pulse width changes from 0.2 ms to 0.4 ms. And then the rate of droplet size growth declines steadily with the increase of pulse width. On the one hand, the volume of liquid flowed through the valve under the same increment of open time decreases due to the reduction of applied pressure. On the other hand, the droplet
volume is proportional to the cube of the droplet diameter. The size errors for some large pulse widths, such as 9 ms, are more obvious. The reason for this result was analysed and considered to be that it is caused by the irregular shape of the large droplet of which was captured in the process of measurement rather than the droplet generator is intrinsically unstable. For the apparent error in pulse width of 0.2 ms, it is caused by the high applied pressure which can lead to the instability of liquid pinch-off.

![Figure 5](image1.png)

**Figure 5.** Effect of pulse width on upper and lower limits of valid applied pressure. The error bar represents the mean absolute deviation.

![Figure 6](image2.png)

**Figure 6.** Effect of pulse width on droplet diameter under the corresponding lower limited valid applied pressure in Fig. 5. The error bar represents the mean absolute deviation.

It can be seen that the droplet generator with a 1.0-mm diameter nozzle can produce the droplets in diameter ranging from about 0.7 to 2.0 mm. Note that the pulse width of 10 ms is not the upper limit to produce droplet. If it is increased continually, the larger droplets may be provided.

4. **Conclusion**

1) An on-demand droplet generator was developed based on a high-speed solenoid valve and investigated experimentally in this paper. The droplet generator can avoid the limitation of the appropriate outlet pressure required at the nozzle tip in most developed droplet generation devices and possesses controllability and stability at the same time.
2) The droplet size can be controlled by the cooperation between the applied pressure and the supplied pulse. When the high-speed solenoid valve is driven by a suitable pulse with fixed width, there correspondingly exists a valid applied pressure range under which a single droplet can be generated.

3) For a given pulse, the droplet diameter increases linearly with the applied pressure as a whole, in spite of small change in size. The wide size range can be achieved by changing the pulse width. It is found that the present droplet generator can produce the droplets in diameter ranging from about 0.7 to 2.0 mm for a given nozzle instead of changing the nozzle diameter [7, 12]. Otherwise, it also can produce droplets smaller than the nozzle diameter [8, 13].

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