A Study on Critical Pulse Conditions for Single-Droplets Generation in Drop-on-Demand Technique

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\textbf{Abstract.} Generating single-droplets is significant for extensive applications of drop-on-demand (DoD) type of piezoelectric inkjet technique (PIT). Based on the mechanism of DoD technique, we theoretically analyze the effects of pulse parameters on the process of droplet generation, and the critical pulse conditions for generating single-droplets are obtained. With a single-droplet generator (SDG) fitted from an inkjet print-head based on DoD technique, we found that upper and lower limit of pulse amplitude for generating single-droplet both changes periodically with pulse width. As the critical pulse width increases, the lower limit has an exponential growth approximately, which is consistent with the theoretical consideration.

\textbf{Introduction}

Droplets generated by piezoelectric inkjet technique (PIT) have wide applications in various fields [1-4]. According to the principle of droplet generation, the PIT can be divided into two types: continuous and drop-on-demand (DoD). The continuous technique is based on the instability and break-up of a cylindrical jet of liquid. Owing to the advantage of high efficiency for generating monodisperse droplets, the continuous technique has been used in generating crowds of aerosol particles, as demonstrated by Berglund-Liu generator [5]. The most striking advantage of DoD technique is that it can generates droplets according to need, so that it can be utilized as monodisperse particle number standard, in which the solid particles are formed by droplets after solvent volatilization [6]. This standard is based on single-droplets generation of the DoD technique, i.e. one ejection corresponding to one droplet without some smaller droplets called satellite droplets. Because the size of satellite droplets is random and uncertain, generating satellite droplets is negative for extensive applications of drop-on-demand technique. Mechanism of droplet formation in DoD technique is complex and relates to various aspects. The dynamics of piezo inkjet print-head operation had been studied and reported by Wijshoff [7]. Droplets ejection in various types of piezoelectric inkjet devices are simulated and studied [8-11]. Liou \textit{et al} discussed the effects of actuating waveform, ink property, and nozzle size on droplets ejection [12]. In general, droplet formation can be analyzed by mechanics and acoustics in the micro fluid. For a definite structure and fluid property of liquid, the only variables remain in a DoD system are pulse parameters, mainly including pulse amplitude and width for a general square pulse. Hence, the effects of pulse parameters on droplet formation in DoD technique are essential for generating single-droplets.

Based on the principle of DoD technique, we theoretically analyze the effects of pulse parameters on the process of droplet generation. The critical pulse conditions for single-droplets generation are analyzed and discussed in theory. To study this issue in experiment, a single-droplet generator (SDG) fitted from an inkjet print-head based on DoD technique is introduced. Generating water droplets with the SDG, the critical pulse conditions for generating single-droplet are obtained in experiment, which may give references for extensive applications of DoD technique.
Theoretical Consideration

Principle of DoD Technique

The structure of a DoD system consists of a vibrating chamber, piezoelectric ceramic plate, and a nozzle and reservoir, as shown in figure 1(a). During operation, owing to the pulses, the piezoelectric ceramic plate deforms rapidly to generate pressure waves in the liquid within the vibrating chamber. When the pressure wave arriving at a nozzle is positive and sufficiently intense, the droplet overcomes the interfacial tension and erupts from the nozzle [13]. The generation, propagation, and reflection of the pressure waves within the vibrating chamber can be seen in figure 1 (b)–(d). At (b), where the pulse rises, the piezoelectric ceramic plate deforms outward rapidly to create a negative pressure wave (−R). At (c), the height of the pulse, this wave propagates towards the nozzle and keeps its sign when reflected by the nozzle, but changes its sign at the reservoir. At (d), where the pulse falls, the piezoelectric ceramic plate returns to create a positive pressure wave +R. If the pulse width is appropriate, R and F can be superposed as shown in figure 1(d). Through the above analysis, the minimum pulse width that can superpose R and F is $2L/c$, where $L$ is the length of the vibrating chamber and $c$ is the propagation velocity of the pressure wave. R can return to its primary state after propagating and reflecting for a distance of $4L$ (one loop), so all the critical pulse widths that can superpose R and F are

$$W_c = p(4L/c) + 2L/c, \quad p = 0, 1, 2, 3... \quad (1)$$

In equation (1), $p$ is the number of loops, taking a natural number. R and F are superposed more strongly when the pulse width satisfies equation (1), while they are superposed more weakly when pulse widths are between two neighboring values in equation (1). In addition, larger $p$ leads to longer propagation distance for R and more reflections; therefore, larger pulse width weakens pressure wave superposition of R and F because of attenuation.

![Figure 1](image)

Figure 1. (a) Simplified structure of a DoD system and generation, propagation, and reflection of the pressure waves in the vibrating chamber at (b) pulse rising time, (c) the height of the pulse, (d) pulse falling time.

Effects of Pulse Parameters on Droplet Formation

The cause of droplet formation is the pressure wave in vibrating chamber. Weak-intensity pressure waves cannot generate droplets, while pressure waves with too high an intensity may lead to form a long cylindrical liquid that can easily break up into satellite droplets. This means Intensity of the pressure wave arrived at nozzle has a range from $I_l$ to $I_u$ for generating single-droplets, where $I_l$
and \( I_u \) are lower and upper limit respectively. These two critical intensities are definite if the structure of vibrating chamber and property of fluid are certain. Under this consideration, pulse parameters, mainly including amplitude and width, are the only factors affecting intensity of pressure waves. Under a critical pulse width, the intensity of the superposed pressure wave can be expressed as

\[
I = I_0 + I_p = (1 + e^{-\alpha (4p+2)}) I_0 ,
\]

where \( I_0 \) and \( I_p \) are intensities of pressure waves motivated by pulse falling and rising respectively, and \( \alpha \) is the attenuation coefficient when pressure wave propagate and reflect in the micro chamber. Compared to \( I_0 \), \( I_p \) has an negative exponential factor which the index is inversely proportional to the length of vibrating chamber, attenuation coefficient, and the number of loops. \( I_0 \) is the original intensity of pressure waves motivated by pulse falling, so that it just relates to pulse amplitude \( U \), the deformation coefficient \( K \) of piezo ceramic plate and the cross-sectional area \( S \) of the vibrating chamber:

\[
I_0 = \left( \frac{KU}{S} \right)^2 .
\]

With equations (1) to (3), the effects of pulse parameters on intensity of the superposed pressure wave under a critical pulse width can be easily obtained as

\[
I = (1 + e^{-\alpha W}) \frac{K^2 U^2}{S^2} .
\]

For generating single-droplets, intensity of pressure wave should satisfy the range from \( I_l \) to \( I_u \), so that the critical pulse amplitudes for generating single-droplets under the critical pulse widths can be expressed as

\[
U_c = \frac{S}{K} \sqrt{\frac{I_c}{1 + e^{-\alpha W}}} ,
\]

where \( I_c \) is the two critical intensities of pressure wave, including \( I_l \) and \( I_u \). Equation (5) shows that under critical pulse widths for generating single-droplets, the critical pulse amplitude has positive correlation with critical pulse width. With some approximations, the relationship can be expressed to exponential functions as \( a \exp(bW_c) + x \), where \( a, b \) and \( x \) are four parameters relating to the structure of vibrating chamber and the fluid properties of liquid.

Analysis above shows the critical pulse amplitudes for generating single-droplets under critical pulse widths. For a general pulse width, the critical pulse amplitudes should be higher because of non-superposition of pressure waves. Besides, critical pulse amplitudes would show a period variation with pulse width as the principle of DoD technique predicted above, in spite of the exponential changes caused by attenuation. In general, single-droplets generation in a DoD system can be accomplished by adjusting pulse parameters to fit critical pulse conditions.

**Experimental Analysis**

**Experimental Apparatus**

To analyze critical pulse conditions for single-droplets generation in DoD technique experimentally, an inkjet print-head based on DoD technique is fitted to an SDG, as shown in figure 2(a). The nozzle plate is the core part of the inkjet print head, containing micro vibrating chambers. There are more than one hundred nozzles in two columns on the front side of the nozzle plate, all of which have diameters of 20 \( \mu \)m. Each nozzle has a corresponding piezoelectric ceramic membrane on the rear side of the nozzle plate. When the inkjet print head is fitted, positive and negative poles of a
piezoelectric ceramic membrane communicate with fine wires to allow control of a single nozzle. The nozzle plate is then fixed back to its original position to keep the liquid channel smooth. Finally, 0.1-mL injectors are connected to the ink filters of the print head as reservoirs.

![Diagram of inkjet print head](image)

Figure 2. (a) Fitted inkjet print head as an SDG. (b) Sectional schematic of the micro vibrating chamber.

The nozzle plate includes a vibration layer, transition layer, communication layer, and nozzle layer, as shown in figure 2(b). The through-holes of these four layers form a micro vibrating chamber, a part of whose wall is the piezoelectric ceramic membrane. The length of the vibrating chamber (2.1 mm) is approximately denoted by the dashed line in figure 2(b). When water droplets are generated by this SDG, based on equation (1) and the propagation velocity of the pressure wave (1.5 km/s), the critical pulse widths are 2.8 \( \mu \)s, 8.4 \( \mu \)s, 14 \( \mu \)s, and 19.6 \( \mu \)s when \( p = 0, 1, 2, 3 \), respectively, where the interval is 5.6 \( \mu \)s in theory. To observe and analyze the ejecting process of water droplets at the nozzle of SDG, a high-speed camera was used through a shadow micro-imaging optical path.

**Results and Discussions**

Driven by different pulse parameters, three possible outcomes result when using the SDG, as shown in figure 3, in which (a) is no droplets, (b) is single droplets, (c) is multiple droplets. The last means a state involves a main droplet accompanied by multiple smaller droplets called satellite droplets. Figure 3 (a)-(c) are aligned by different images captured by the high-speed camera in chronological order, for easily understanding the ejecting process of droplets at nozzle. The inter-frame time \( \Delta t \) is 3.3\( \mu \)s. The pulse amplitudes in (a), (b) and (c) are 9V, 10V and 11V, respectively, at a pulse width of 9.8 \( \mu \)s. It can be seen in (a) that the tip of liquid column forms a droplet, while it cannot escape from liquid body since the kinetic energy is too small to overcome surface energy. Then the droplet returns back to form a meniscus and has residual oscillations. When pulse amplitude is appropriate, as shown in (b), the tip of liquid column can break away from liquid column to generate a single-droplet with a speed. However, continue to increase the pulse amplitude leads liquid column to have a long tail which then breaks to a smaller satellite droplet, as shown in (c). The main droplet that formed by tip of liquid column in (c) is so fast that smearing appears, with exposure time of 3 \( \mu \)s.
To find the critical pulse conditions for single-droplet generation, the ejecting processes of droplets under different pulse amplitudes and widths are observed and the states are recorded, as shown in figure 4. In the experiment, the range of the pulse width was 0–25 µs in increments of 0.2 µs and the range of pulse amplitudes was 0–20 V in increments of 0.2 V. Figure 4 shows that, at a constant pulse width, the droplet generation state changes from no droplets to single droplets and then to multiple droplets with increasing pulse amplitude. The range of pulse amplitude corresponding to the single-droplet state is small, as illustrated by the narrow band of single-droplets state. The narrow band changes periodically with pulse width, which is consistent with theoretical analysis above. The pulse widths of A (3.2 µs, 10 V), B (9.8 µs, 10 V), C (16 µs, 12 V), and D (23.2 µs, 15 V) in figure 4 are four critical pulse widths that can superpose pressure waves strongly, corresponding to \( p = 0, 1, 2, \) and 3, respectively. The interval of these four pulse widths was 6.6 µs, which differs by 1 µs from the theoretical value of 5.6 µs predicted previously. The error may arise from the theoretical approximation, in which the vibrating source is considered to be a point whereas it is actually a long membrane in the SDG.

Figure 4. Different droplet generation states for a range of pulse width and amplitude. The exponential curve is fitted by the lower limit of amplitude under critical pulse widths.

Under critical pulse widths shown in figure 4, the critical pulse amplitudes increase with pulse width, which the lower limit approximately fits a general exponential function as the curve shows, with parameters \( a, b \) and \( x \) are 1, 13 and 8 respectively. The fitted curve is just used to demonstrate the tendency of relationship between critical pulse amplitude and width. In fact, the parameters of the exponential function have complicated relations with various factors in DoD technique, such as structure of vibrating chamber and fluid property of liquid. The parameters of the exponential function are difficult to obtained exactly, and they may have great differences in various DoD systems. Besides, the waveform of pulse also has important effects in DoD technique, in spite that
critical pulse conditions of a general square pulse for generating single-droplets is focused in this work.

Summary
By analyzing propagating process of the pressure wave in a DoD system, the theoretical expression of critical pulse conditions for generating single-droplets are obtained. With a single-droplet generator fitted from an inkjet print-head based on DoD technique, we found that single-droplets state forms a narrow band and changes with pulse width periodically. The lower limit of pulse amplitudes for generating single-droplets exponentially increases with critical pulse width approximately, which is consistent with the theoretical consideration. This may give references for the extensive applications of DoD technique for generating single-droplets.

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