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NBS TECHNICAL NOTE 776

A New Method for Generating Waterdrops of Specified Mass

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A New Method for Generating Waterdrops of Specified Mass*

James E. Potzick

A waterdrop generator has been constructed, based on the mechanical resonance of a vibrating waterdrop, which can generate drops of 1.5 to 37 mg with standard deviations in the range of 0.1 percent to 10 percent of drop mass. Drop mass over this range and drop interval are remotely controlled.

Key words: Drop generator; liquid drop; waterdrop.

1. Introduction

Water is one of the most useful and abundant substances on our planet and is the subject of a great deal of research. Much has been written concerning the behavior of waterdrops [1-5]**, and in preparation for a study continuing this research, a new type of waterdrop generator was developed using what is believed to be a hitherto unexploited operating principle.

Most waterdrop generators seem to fall into three categories. The simplest type allows water to drip from the end of a capillary tube [1,6]. The size of the drop depends primarily on the outer diameter of the tube. This type of generator is characterized by simplicity, excellent repeatability of drop size, and lack of flexibility.

A more sophisticated type of waterdrop generator is based on a phenomenon described by Rayleigh [7] nearly a century ago in which a jet of water issuing from a capillary tube is broken into uniform drops by vibrating the capillary at the proper frequency [8,10-14]. This produces a continuous stream of drops whose separation is on the order of a drop diameter. The size of the drops depends primarily on the flow rate and the diameter of the tube, and, over a narrow range, on the frequency of vibration.

In addition, there are other types of waterdrop generator which use some means such as an air blast [15,16], rapid acceleration of the capillary tube, or electrostatic force [9] to detach a drop of given size from the end of a capillary tube.

While each of these waterdrop generators has its merits, a more flexible generator is needed for the impending study, with the following properties: drop size and interval between drops must be remotely controlled so the generator can be located where access is difficult; drop size must be continuously adjustable; uncharged or arbitrarily charged drops must be available for studies of electrostatic effects; the time interval between drops must be variable from several seconds to infinity, i.e., single drops must be available on demand.

A waterdrop generator has been developed which meets all of these requirements to a reasonable degree. In this generator water is allowed to drip from a nozzle as in the first type of generator described above, but to generate drops of arbitrary size the nozzle is vibrated vertically at a low frequency while the drop is slowly growing at the end of the nozzle. When the resonant frequency of the drop approaches the vibrating frequency, the drop falls. For a given nozzle the mass of the drop is determined by the frequency of vibration, and the present apparatus can generate drops from 1.5 mg to 37 mg with a standard deviation from 10 percent to 0.1 percent of drop mass, with one nozzle. Other mass ranges can be covered with different size nozzles. A remotely actuated solenoid valve can be used to stop the water flow between drops. One might object that the drop continues to vibrate while it is falling, but this is true of drops generated by other methods as well [3,7,17], and is an important consideration in the study of water drop impacts. The vibrating pendant waterdrop may be useful in other areas of water research, such as in studies of surface properties or viscosity measurements. And of course other liquids besides water can be used.

*This research is part of a study sponsored by the Fluid Dynamics Program, Office of Naval Research, Department of the Navy, Arlington, Virginia 22217.

**Figures in brackets indicate literature references at the end of this paper.

2. Principle of Operation

Figure 1 shows a waterdrop hanging from a nozzle. If the nozzle vibrates vertically with a small amplitude, the vibrating drop will assume the shapes shown in the sketch, figure 2; one might say the drop appears alternately squeezed and stretched. At a sufficiently large amplitude the neck of the drop in the "stretch" position will go to zero diameter and the drop will fall. This could be called an infinite amplitude state.

The resonant frequency of the pendant drop is a monotonic function of its mass. In operation the amplitude of the nozzle vibration is chosen and kept constant so that, as the drop mass grows slowly, its amplitude grows and reaches the infinite amplitude state as its resonant frequency approaches the operating frequency. In this way the mass of the falling drop is chosen by selecting the frequency of vibration. Figures 3 and 4 show water drops vibrating near their resonant frequencies at 40 and 90 Hz, respectively.

Note that this method of generating waterdrops is different from Rayleigh's method, since he writes of periodic disturbances propagating down a falling stream of water, breaking it into drops, and there is no stream here, the drops forming individually at arbitrarily long intervals. At zero frequency, of course, the vibrating waterdrop generator is identical with the stationary capillary tube type described above. Mason, et al. [13], write of their vibrating hypodermic needle apparatus that the needle may undergo several cycles at low flow rates before a drop is dispatched, but they were primarily interested in Rayleigh's method, and their frequency was fixed.

No analytical treatment of the vibrating drop is attempted here.

3. Description

The apparatus is shown in figures 5 and 6. A small moving coil vibrator is connected to the stainless steel armature and nozzle by a flexible link made from a piece of plastic tubing. The armature slides vertically in a brass bearing and is lubricated with a thin film of light oil to reduce distortion in the sinusoidal motion due to Coulomb friction. An air bearing could be used here to advantage. There is a small permanent magnet inside the armature and a wire coil wound around the brass bearing so that the motion of the armature can be monitored by observing the voltage across the coil.

Interchangeable nozzles are screwed into the bottom of the armature and water is supplied from the reservoir through a short length of very small rubber tubing of the kind used to supply ink to recorder pens. This tubing slips over a piece of hypodermic needle which is press-fitted into the armature. Water is supplied by gravity feed from a reservoir located above the apparatus through a flow regulating needle valve and a remotely controlled solenoid shutoff valve.

The nozzle is made of stainless steel and has a flat bottom of 2.3 mm diameter, with a sharp edge. The hole is 0.34 mm diameter (No. 80 drill), and the conical side of the nozzle is polished. A hemispherical tip was tried for the nozzle, but the extent of the surface which the water was to wet was then not well-defined; about twice the vibration amplitude was needed to generate drops, and only a small range of drop sizes could be accommodated. After the drop has left the nozzle it falls between a photocell and lamp, generating an electrical pulse which signals its arrival.

A block diagram of the system is shown in figure 7. A digitally tuned oscillator is used to facilitate accurate and repeatable frequency setting. This oscillator drives the vibrator through an amplitude regulator and power amplifier. The low voltage signal from the monitor coil is amplified and used to monitor the amplitude and waveshape of the armature motion. A differential amplifier must be used here to avoid pickup from the vibrator drive current in the long cable to the waterdrop generator.

There is some small dependence of the waterdrop mass on vibration amplitude (see below) and so an amplitude regulator, based on a design described previously [18], is used to hold the monitor coil voltage to a constant amplitude. When the vibrator is turned on, for instance, the armature motion warms the oil, reducing its viscosity. Without the regulator the vibration amplitude would increase. The regulator cannot be used at frequencies below

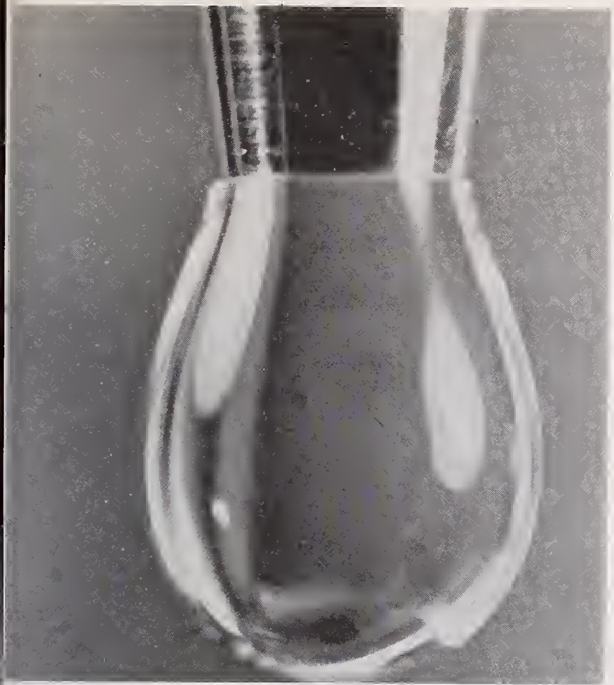

Figure 1. Stationary waterdrop hanging from nozzle.

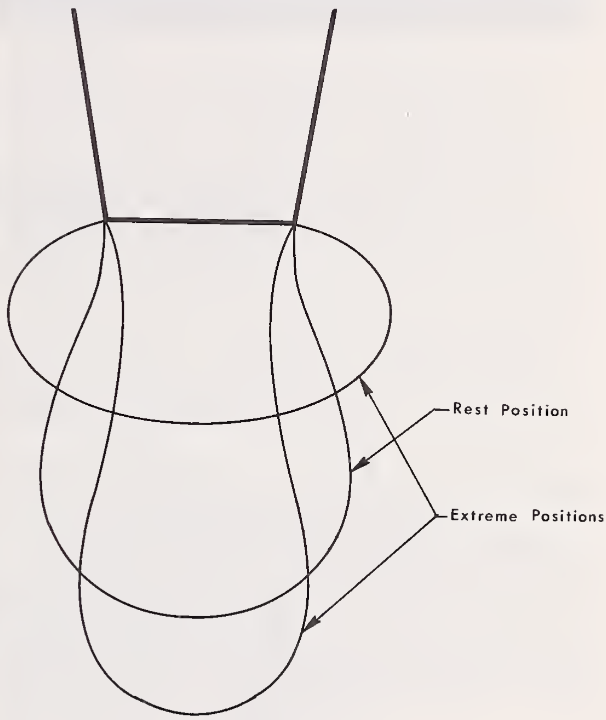

Figure 2. Sketch of vibrating waterdrop in its simplest mode of vibration near its resonant frequency.

Figure 3. Vibrating waterdrop at 40 Hz shortly before detachment - incipient 6.8 mg drop.

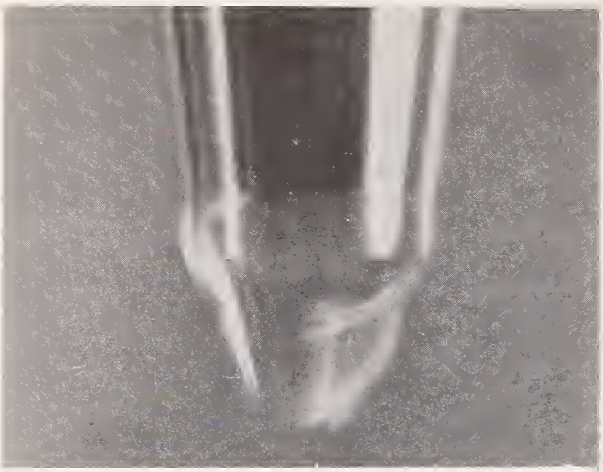

Figure 4. Vibrating waterdrop at 90 Hz shortly before detachment - incipient 1.5 mg drop.

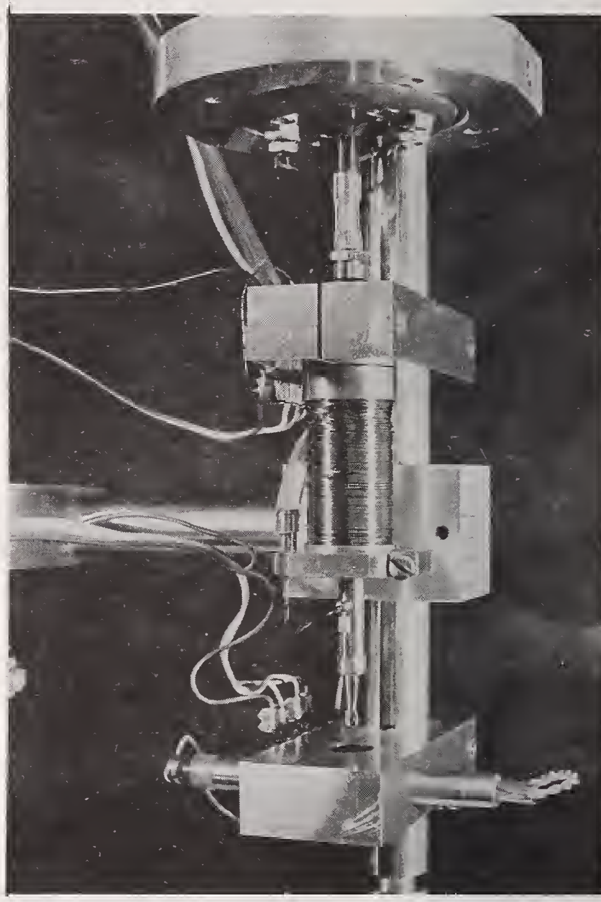

Figure 5. Photograph of waterdrop generator. Vibrator is not seen in this view.

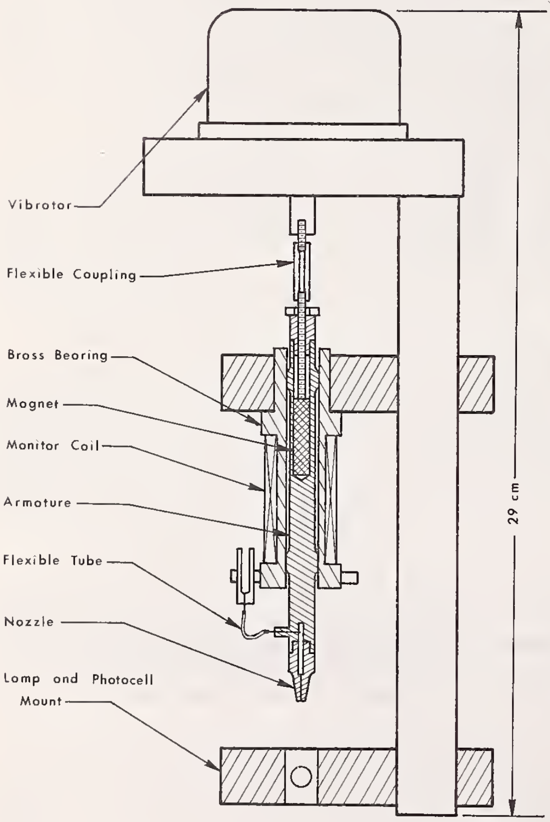

Figure 6. Mechanical construction of waterdrop generator.

about 10 Hz.

The apparatus can generate waterdrops continuously (at intervals of several seconds) by leaving the vibrator on and the solenoid valve open. A single drop mode, or "demand mode," can be used, however, in which a single drop is generated when the "Initiate" button is pushed. This sets the flip-flop in figure 7, opening the solenoid valve and turning on the vibrator. When the drop falls the photocell generates a pulse which resets the flip-flop, closing the valve and turning off the vibrator. This pulse is also useful for announcing the approach of the waterdrop to downstream equipment.

4. Performance

Ordinary distilled water was used during calibration of the waterdrop generator. The flow rate was adjusted with the needle valve to about 37 mg/min and seemed to be independent of the waterdrop mass. The only apparent requirement on the flow rate is that it be low enough so that each drop grows slowly compared to the transient motions that occur at detachment and forming of a new drop.

It would seem that at each frequency there should be an optimum amplitude of vibration at which drops form reliably and uniformly. Obviously at zero amplitude one obtains the largest drops regardless of frequency; on the other hand, if the amplitude is too large, drops will be flung off the nozzle before they have a chance to resonate. Figure 8 shows two curves of drop mass as a function of amplitude, the results of a little experiment in which drops were formed over a range of vibration amplitudes at each of two fixed frequencies. The curve for each frequency is discontinuous, and where the segments overlap the probability that a drop will fall on the lower segment increases with increasing amplitude. In normal operation the amplitude is chosen so that the lowest segment is used. Note there is some small slope to the curve here so that the mass depends to some extent on amplitude as well as frequency. In the present case the amplitude was chosen rather arbitrarily and is shown in figure 9. If the optimum amplitudes were known, a frequency response network could be inserted in the vibrator control circuit to insure that the optimum amplitude is used at each frequency. This would probably improve the waterdrop generator's performance.

In calibrating the generator 200 waterdrops were generated and weighed over a period of eight days at ten frequencies from 0 to 90 Hz. Each drop was caught in a small aluminum pan, covered with a small inverted aluminum cup to discourage evaporation, and weighed on an analytical balance to a resolution of 0.1 mg. The zero offset of the balance was checked and readjusted after every 3 to 5 drops and this drift error was assumed to be distributed linearly over these drops, whose weights were correspondingly adjusted. The apparatus was generating drops continuously, so that only every fifth drop or so was weighed. When the demand mode is used it is recommended that several drops be generated and discarded before one is used so that neither too much nor too little water is on the nozzle as the drop begins to form. Then, of course, the continuous mode calibration will apply.

In generating waterdrops by various methods a small droplet called a satellite is sometimes formed with the drop [7,10,11,19]. During calibration of the waterdrop generator satellites were seen in the weighing pan about 15 percent of the time (if a satellite falls on top of the drop it would not be seen). In each case the mass of the satellite was estimated to be less than 1 percent of the mass of the drop.

The lateral scatter of the falling drops appears to be fairly low, since they nearly all fell into the center of the weighing pan, which was placed in the same position each time. The larger drops have less lateral scatter than the smaller ones.

The results of the waterdrop generator calibration are presented in table 1, where the daily average masses $\overline{m_i}$ (where i refers to day 1 through 5) are given for drops at ten frequencies on five different days. All of the drops which were collected and weighed are included. The pooled average mass $\overline{m_p}$ at each frequency is the average of the five $\overline{m_i}$'s. The pooled corrected standard deviations were calculated from

$$\sigma_{pc} = \sqrt{\sum_{i=1}^{5}\left(\sigma_i^2/5\right) - \sigma_w^2}$$

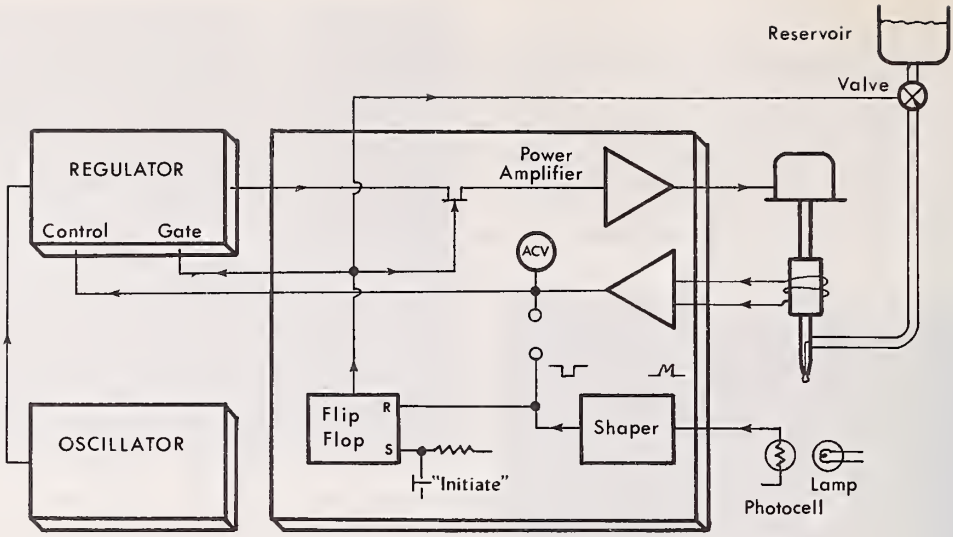

Figure 7. Block diagram of control circuitry.

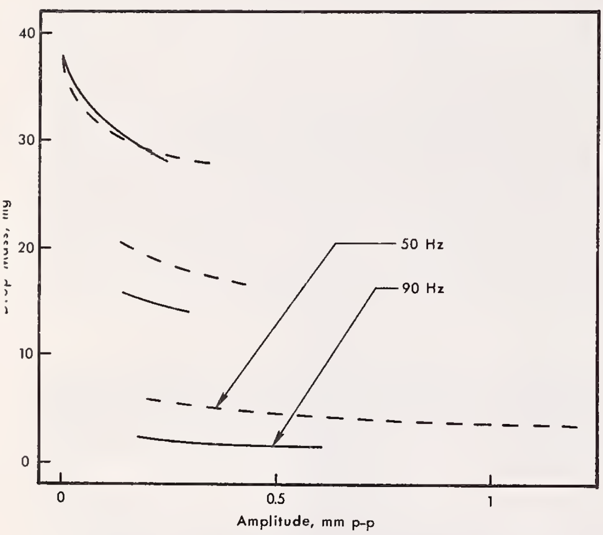

Figure 8. Variation of waterdrop mass with vibration amplitude at two fixed frequencies.

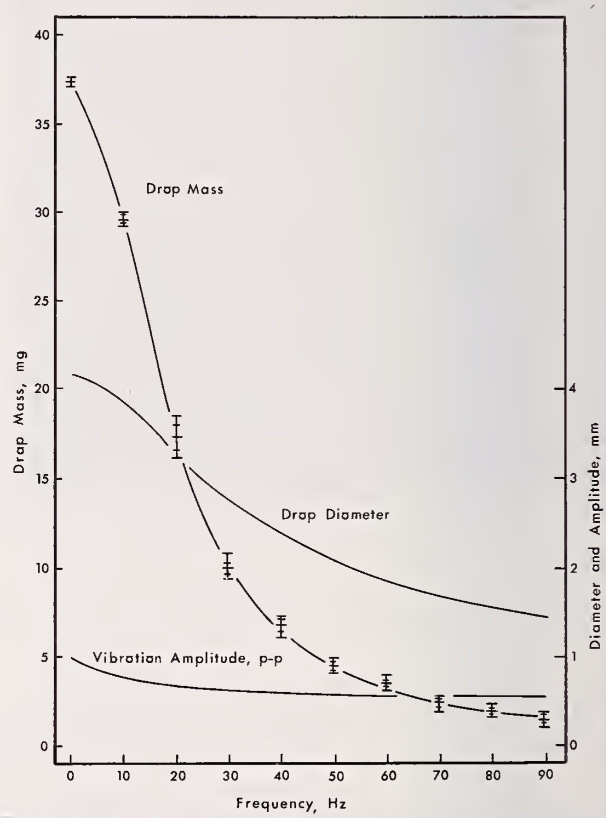

Figure 9. Waterdrop generator calibration data. Extreme bars at each date point represent extreme values of mass found at each frequency during calibration.

where the σ_i are the daily standard deviations at each frequency, and σ_w is the standard deviation of the weighing process, estimated to be 0.09 mg by weighing a 4.4 mg piece of wire several times and calculating the standard deviation. Note that on a percentage basis the standard deviations of the radii are one third the standard deviations of the masses reported in the table, since dm/m = 3 dr/r for a sphere; that is, the standard deviations of the radii range from .03 percent to 3.4 percent of the mean radii. The last two rows of the table show the drop diameters and the number of drops included in the data.

The calibration data are shown graphically in figure 9, where drop mass is plotted with respect to vibration frequency. The center bar at each data point represents the pooled average mass from table 1; the extreme bars represent the heaviest and lightest of all the drops generated at each frequency during calibration; and the other two bars represent the σ_{pc} from the table. Also shown in figure 9 are the vibration amplitude and the equivalent diameters for spherical drops.

To obtain further evidence of the resonant nature of the drop detachment process a small amount of water was admitted to the nozzle tip and then the flow stopped. The nozzle was then vibrated at the prescribed amplitude and the frequency swept toward the resonant frequency of the drop until the drop fell. Then the drop was weighed and the frequency recorded. The results are shown in table 2, where the calibration frequency is taken from figure 9 for the listed drop mass. Note that in most cases the drop fell slightly too soon (i.e., the nozzle frequency at detachment was too low when the frequency was swept upwards and too high when swept downwards). This probably indicates that the vibration amplitude was slightly higher than optimum. Some difficulty is encountered in the downward sweep, since the drop first must grow while the nozzle is still, then the nozzle vibration must grow slowly in amplitude without exciting higher modes of vibration of the hanging drop and causing it to fall.

In addition, observation under stroboscopic light confirms that the hanging waterdrop oscillates, with growing amplitude as the drop grows in mass, in the manner illustrated in figure 2. Furthermore, with the nozzle amplitude fixed below that required for detachment of the drop, the drop amplitude can be seen to grow, pass through a maximum, and then diminish as either the drop mass varies or the nozzle frequency varies sweeping the resonant frequency through the nozzle frequency or vice versa.

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Table 1. Waterdrop generator calibration data.

	Vibration Frequency, Hz									
	0	10	20	30	40	50	60	70	80	90
Day	Daily Average Mass, mg ($\overline{m_i}$)									
1	37.37	29.78	17.66	10.08	7.00	4.43	3.70	2.20	1.83	1.30
2	37.47	29.78	17.08	10.24	6.53	4.60	3.52	2.47	1.97	1.60
3	37.43	29.68	17.72	10.34	7.10	4.47	3.64	2.63	2.10	1.62
4	37.50	29.82	17.80	9.96	6.73	4.70	3.66	2.67	2.20	1.56
5	37.27	29.60	16.92	10.08	6.87	4.60	3.52	2.63	1.87	1.50
$\overline{m_p}$	37.408	29.732	17.436	10.140	6.846	4.560	3.608	2.520	1.994	1.516
σ_{pc}	.033	.204	.710	.337	.383	.248	.141	.218	.118	.153
$\sigma_{pc}/\overline{m_p}$	0.09%	0.69	4.07	3.32	5.59	5.44	3.90	8.63	5.91	10.10
Drop Dia.	4.15 mm	3.84	3.22	2.69	2.30	2.06	1.90	1.69	1.56	1.43
No. of Drops	15	25	25	25	15	15	25	15	15	25

Table 2. Drop detachment with swept nozzle frequency.

Drop Mass	Nozzle Frequency	Calibration Frequency	Sweep Direction
11.1 mg	27.8 Hz	28.5 Hz	Up
10.6	28.1	29.0	Up
5.7	42.8	44.0	Up
16.0	22.4	21.3	Up
18.0	23.4	19.3	Down
24.6	19.1	14.2	Down
17.6	21.6	19.7	Down

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16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

A waterdrop generator has been constructed, based on the mechanical resonance of a vibrating waterdrop, which can generate drops of 1.5 to 37 mg with standard deviations in the range of 0.1 percent to 10 percent of drop mass. Drop mass over this range and drop interval are remotely controlled.

17. KEY WORDS (Alphabetical order, separated by semicolons)

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