Producing Droplets Smaller than the Nozzle Diameter by Using a Pneumatic Droplet Generator

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Abstract
A pneumatic droplet generator to produce water/glycerin droplets smaller than the nozzle diameter is described. The generator consists of simple brass and stainless steel tubes and junctions. A small nozzle is press-fit into a liquid-filled nozzle holder, attached to the generator via a nut and the system is connected to a gas cylinder through a solenoid valve. Opening the valve for a preset time sends a pressure pulse to the liquid and ejects a single droplet. Then, the gas in the generator escapes through an exit vent tube, so that the pressure drops rapidly and no further droplets emerge. To produce these droplets, we created the required pressure variation within the droplet generator by using different tube lengths at the exit vent. Also, the effect of various experimental parameters, such as the gas supply pressure, nozzle size, pressure pulse width, and glycerin concentration on droplet formation was investigated. It was observed that small droplets could not be generated when the viscosity was too low or too high and depending on the nozzle size and liquid properties different ranges for the Ohnesorge number was obtained. By using this method droplets with diameters 65% the nozzle diameter could be produced and it may be possible to produce small droplets from other liquids provided that the corresponding Ohnesorge number is in the range of the Ohnesorge number obtained for the experimental system.

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**Introduction**

In recent years, extensive research has been done on different techniques to produce microdrops of desired diameters on demand. Such methods are used in a large number of scientific and industrial applications, such as inkjet printing, inkjet soldering, IC manufacturing, biological assays, and many other fields. Some drop-on-demand ejectors, for example, electrohydrodynamic ejectors, produce droplets smaller than the nozzle diameter by pressurizing the liquid, so that a convex meniscus is formed. When an electric field is applied, the meniscus transforms into a sharp cone. If the electric field strength is high enough to overcome the surface tension of the meniscus, the tip of the meniscus breaks free and forms a droplet. Depending on the electric field, duration and amplitude of the ejection pulse, droplets much smaller than the nozzle diameter can be produced [1]. Another example is the focused ultrasound ejector which works by focusing an ultrasonic radiation pressure from a lensed transducer to eject a droplet from a fluid-air interface. By shifting the distance between the liquid and transducer the size of the ejected microdrops can be varied dynamically [1].

Recently, piezoelectric droplet generators have also been used for this purpose. The voltage pulse shape used to excite the piezoelectric element, has various effects on the drop ejection process. Using different vibrational modes over the ejection nozzle can affect both the size and direction of microdrops [1] and varying the pulse width generates fluid jets with different diameters. Applying more sophisticated manipulations of drive parameters, including sequential excitation of negative-positive-going pressure pulses, can similarly modulate the diameter of microdrops.

By using a piezoelectric inkjet, Sakai [2, 3] applied controlled sequential negative-positive-going pressure pulses to alter the diameter of droplets. A negative impulse was initiated to draw the fluid in the nozzle inward. While the fluid was in motion, a properly timed positive pressure was applied causing the central region to be accelerated outward at a higher rate than the liquid in the vicinity of the nozzle walls. By applying the above technique he could obtain small ink droplets with diameters about 20% the nozzle diameter.

Chen and Basaran [4] investigated the formation of small water/glycerin droplets using a piezoelectric ejector with a “squeeze mode” nozzle consisting of a piezoelectric transducer bonded outside of a glass capillary tube with a 70 μm diameter. They applied a sequence of negative-positive- and again negative going voltage pulses. During the first negative voltage, the piezo expanded and liquid was drawn back into the nozzle; during the positive voltage pulse, a “tongue” emerged from the tip of a primary drop (the about to form droplet) with a high velocity relative to the liquid nearby; and finally, during the second negative pulse, the primary drop was suppressed and the tongue broke up and formed a small droplet (Fig. 1). Using this method, water/glycerin droplets with diameters less than 50% the nozzle diameter were produced. Also, to specify a range for glycerin concentrations within which a tongue was formed, the dimensionless Ohnesorge number was defined as

\[
Oh = \frac{\mu}{\sqrt{\rho R \sigma}}
\]

where \(\mu\), \(\rho\), and \(\sigma\) are the viscosity, density, and surface tension of the liquid, respectively, and \(R\) is the nozzle radius. Experimentally, they found that if the viscosity is too high or too low, small drops can not be formed. For intermediate values of the Ohnesorge number (0.1-0.2 for 50-61 wt% glycerin concentration), there will be a region near the interior wall of the nozzle where the viscous drag is important, and an inviscid core region near the centerline (Fig. 1). Thus, in the vicinity of the centerline, the meniscus protrudes out of the nozzle with a deformation in phase with the pressure pulse and near the wall it moves inward and is out of phase with the pressure.

Ulmke et al. [5] studied the production of single droplets with different diameters using double-distilled water and a mixture with 50 wt% glycerin in a piezoelectric droplet ejector. Droplets were generated from a capillary system filled with liquid and enveloped by a piezoceramic tube. Switzer [6] produced uniform-size liquid droplets by operating a piezoelectric droplet generator at different operating modes. When applying the drop-on-demand-mode, droplets with diameters the same size as the nozzle diameter were produced. Considering the direct relationship between the droplet diameter, piezoelectric voltage, and liquid pressure, the droplet diameter could be varied.

Cheng et al. [7] and Foutsis [8] used a pneumatic drop-on-demand generator, originally developed by Chandra and Jivraj [9], to produce tin droplets. During his experiments, Cheng [10] observed irregularly sputtering, and small droplets emerged 10-15 ms after a large droplet was ejected. In further investigations, Foutsis [8] produced single and multiple small droplets ranging from 32-88 μm and 23-88 μm in diameter, respectively, by using a 102 μm diameter nozzle.

In this paper a pneumatic droplet generator is described in which rapidly opening and closing a solenoid valve applies gas pressure pulses to the liquid inside a nozzle holder forcing droplets out of a nozzle. The generator is originally developed and patented by Chandra and Jivraj [9] which has no moving parts, and is simple to build, robust and suitable for high temperature liquids. Compared to this generator, the present system is
lighter and easier to assemble and disassemble and because of its simplicity, it is easier to refill the nozzle holder when required.

**Experimental Method**

The main body of the droplet generator consisted of a simple brass T-junction with a Tube O.D. of 25.4 mm. Figs. 2 and 3 show a photograph and a schematic diagram of the experimental apparatus, respectively. Three different nozzle sizes were used: a 0.204 mm diameter nozzle (Model 2-80-008, Swiss Jewel Company, Philadelphia, PA); a 0.102 mm diameter nozzle (Model 0102T47, Swiss Jewel Company, Philadelphia, PA); and a 0.051 mm diameter nozzle (Model 0051T47, Swiss Jewel Company, Philadelphia, PA). Each nozzle had a tapered cross section ending up in a short cylindrical hole (Fig. 4). The sizes of nozzles, the dimension tolerances and the aspect ratio of each of them are listed in Table 1. It can be observed that smaller nozzles (51 and 102 μm in diameter) may have larger aspect ratios than a larger nozzle (204 μm in diameter). Each nozzle was press-fit into an Aluminum nozzle holder, which was filled with liquid and attached to one of the outlets of the T-junction (droplet generator main body) using a female nut with a Tube O.D. of 25.4 mm (Fig. 5). The second outlet of the T-junction was connected to a pressure transducer to measure the pressure variation inside the droplet generator. Finally, the third outlet was connected to the gas supply line and exit vent via a T-junction.

Droplets were forced out of the droplet generator by applying pulses of pressurized oxygen free nitrogen gas (O2 less than 5 ppm, BOC, Mississauga, ON) to the liquid inside the generator. The pressure of the nitrogen supply line was maintained in the range of 34.5-276 kPa, and the pressure pulse was delivered by activating a solenoid valve. In order to produce small droplets, a fast response solenoid valve (HSO2L6H50B, Numatics, Highland, MI) with a response time of 8ms to fully open was used.

To relieve the pressure inside the droplet generator rapidly, the gas line was connected to the generator through a T-junction and the other outlet acted as a vent to which a 24.5 or 12 cm long stainless steel tube with an I.D. of 4.8 mm was connected. To measure the pressure variation inside the droplet generator, a high speed dynamic pressure transducer (Type 601B1, Kistler Instrument Corporation, New York) was used. The signal from the pressure transducer was sent to a Dual Mode Amplifier (Type 5010, Kistler Instrument Corporation, New York). Then, it was input to the analog input channel of a Lab VIEW control system, so that the pressure variation inside the droplet generator could be read and analyzed by the computer.

To photograph droplets emerging from the nozzle, a CCD camera, Sensi Cam High Speed (Type 370 KF, OPTIKON Corporation, Kitchener, ON), was used. The CCD chip was capable of recording 30 frames per second with a resolution of 1280x1024 pixels and an exposure time as low as 100 ns. Controlling software, CamWare, was also used to adjust the camera’s parameters and start the system. The camera was equipped with a Tamron lens (Tamron AF SP 90/2.8 Macro, Japan) with a minimum object distance of 0.29 m. The photographing system also included a light source, a 60 watts/120 volts light bulb, placed close to the droplet generator (Fig. 3).

The Lab VIEW Control System with a data acquisition board (PCI-MIO-16E-4, National Instruments, Toronto, ON), and an I/O connector (SCB-68, National Instruments, Toronto, ON) controlled timing of signals for the camera, solenoid valve, and pressure transducer. To monitor the rapidly changing pressure inside the droplet generator, the data acquisition was chosen to be 5000 samples/sec for a duration of 50 ms for each pressure pulse. Hence, 250 samples were obtained from the pressure transducer in each pulse.

Initially, the nozzle holder is filled with liquid. When the solenoid valve is opened for a pre-set time (pressure pulse width), nitrogen gas flows into the droplet generator, increases the pressure inside the generator and forces liquid out of the nozzle. Once the liquid jet emerges from the nozzle, it breaks up into droplets due to fluid instability. Then, the gas inside the droplet generator escapes through the venting tube, and a negative pressure is produced, withdrawing back the remainder of the liquid jet. No further droplets are generated until another pressure pulse is applied. By adjusting the pulse width, the opening time of the solenoid valve and hence, the pressure build-up duration in the droplet generator can be varied. In all experiments, the nozzle holder is completely filled with liquid (distilled water was used in mixtures), and the ejection rate is set to 0.5 Hz. The exit vent is kept fully open, except where specified.

**Results and Discussion**

**Water Droplets**

Formation of water droplets using a pneumatic droplet generator was previously investigated by Cheng [10]. Single water droplets were produced from a 102 μm diameter nozzle with diameters almost twice the nozzle diameter. In the present study, to generate small water droplets (~ 100 μm in diameter), a 51 μm diameter nozzle was used. Based on previously published results [11], it was expected that the droplet diameter would be approximately twice the jet diameter; however, experiments showed different results and single droplets with diameters 4-5 times the nozzle diameter, were produced during the first peak pressure. One possible reason for this discrepancy could be the aspect ratio of the nozzle. For this case, the supply pressure...
and pulse width were set to 103.5 kPa and 8.815 ms, respectively, and instead of a vent tube, a conical shape aluminum vent with a 1.75 mm diameter hole in the center was connected to the droplet generator by using a nut.

It was observed that during droplet formation, the outer surface of the nozzle was wetted by the liquid right at the nozzle exit. To reduce or even eliminate this liquid accumulation, one possible method was to increase the negative pressure within the generator, which withdraws the liquid back into the generator and prevents further liquid ejection. Experiments showed that connecting a tube at the exit vent increases the negative pressure. Fig. 6 shows the effect of a 24.5 cm long vent tube on pressure variation within the droplet generator. When using the 24.5 cm long vent tube, no droplets emerged for supply pressures less than 207 kPa. However, at 207 kPa, when the pulse width was varied from 8 to 14 ms, a little tongue emerged during the first two peak pressures and was withdrawn back during the negative pressure.

Because the 51 μm diameter nozzle was easily clogged, larger nozzles were used. For a 204 μm diameter nozzle, a 24.5 cm long tube was connected to the exit vent, and the supply pressure was set to 34.5 kPa. It was observed that for a 6.8 ms pulse width, a main droplet emerged during the first peak pressure, and irregular sputtering occurred during the second peak (Fig. 7). The experiment was repeated for other supply pressures; however, changing pressure did not affect the result.

Water/Glycerin Droplets
When using a 204 μm diameter nozzle and a 24.5 cm long vent tube, different concentrations of glycerin (0-100 wt%) were tested; but, only for solutions with concentrations ranging from 70-90 wt% glycerin, single small droplets were observed. For a 102 μm diameter nozzle, 12 and 24.5 cm long tubes were used with a glycerin concentration range of 0-60 wt%. Tables 2 and 3 show the physical properties of water/glycerin mixtures and the corresponding Ohnesorge number. It can be seen that adding glycerin increases the mixture viscosity and density, but surface tension decreases.

Using a 204 μm diameter nozzle-Fig. 8 demonstrates the formation of a single small droplet followed by a larger droplet, (primary droplet). In this case, the tube length was 24.5 cm, the liquid was a solution with 55 wt% glycerin (Oh= 0.077), and the supply pressure was set to 69 kPa. When a 5.43 ms pressure pulse width was applied, a small tongue emerged from the nozzle over the second peak pressure. The tongue elongated with time and finally detached from the primary drop and produced a small droplet. Because the peak pressure was large enough, the primary drop from which a satellite droplet was about to detach separated as well.

Primary and small droplets could also be obtained at different supply pressures for the same liquid (Fig. 9).

At higher glycerin concentrations, it was possible to eliminate the primary droplet and produce only single small droplets. Fig. 10 shows a single droplet emerging from the nozzle when a solution with 85 wt% glycerin (Oh= 1.038) was used. In this case, the tube length was 24.5 cm and the supply pressure and pulse width were set to 69 kPa and 5.81 ms, respectively. Single small droplets could be also generated at higher supply pressures (Fig. 11). By comparing the pressure variations in Figs. 9 and 11, it can be observed that at higher glycerin concentrations, due to higher viscosity, a larger peak pressure is required. At concentrations higher than 90 wt% (Oh= 1.73), because of high viscosity, it was not possible to generate small droplets. However, in the case of distilled water (Oh= 0.01), due to low viscosity, uncontrollable sputtering occurred during the second peak pressure.

To study the effect of the pulse width on formation of single droplets, a solution with 85 wt% glycerin was used, the supply pressure was set to 10 psig, and the pulse width was increased to 5.937 ms (compare with 5.81 ms in the previous case). It was observed that by using a larger pulse width, more liquid comes out of the nozzle, the emerging tongue grows in diameter, and due to excess of the protruding liquid, the thread which connects the small droplet to the rest of the liquid is not at its maximum length. It consists of two segments, a micro thread followed by a larger thread in diameter (Fig. 12 at time t=1.2 ms). For the shorter pulse width, only the micro thread exists. The shape of the about to form primary drop is also affected by the pulse width. At a higher pulse width, more liquid accumulates at the tip of the nozzle and forms a spherical profile, while for a shorter pulse width, a conical shape is developed (Fig. 10).

Using a 102 μm diameter nozzle-When a 12 cm long tube was used at the exit vent, at supply pressures less than 138 kPa, stable droplet ejection could not be obtained; therefore, a 207 kPa supply pressure was used. In this case, single small droplets could be obtained for glycerin concentrations ranging from 0-50 wt% glycerin (Oh= 0.015 to 0.086); however, with pure water multiple small droplets were produced. With a 24.5 cm long tube the concentrations range was 50-60 wt% glycerin (Oh= 0.086 to 0.15).

Effect of the Exit Vent Tube Length on Formation of Small Droplets
When using a 102 μm diameter nozzle, a 12 cm long vent tube, and solutions with 60 wt% glycerin and higher, small droplets could not be produced. It was expected that increasing the pulse width would produce droplets; therefore, the pulse width was gradually increased from 4.4 ms to 7 ms. The peak pressures in-
increased as well. It was observed that when the pulse width exceeded the value of 5.4 ms, the peak pressures did not grow much further, and the maximum value of peak pressures remained less than 8.3 kPa. On the other hand, when a 24.5 cm long vent tube was applied, single small droplets emerged from the nozzle at a pulse width of 5.1 ms and the second peak pressure had a value of 8.3 kPa, which could be the minimum required pressure to produce droplets from a mixture with 60 wt% glycerin.

When using the 12 cm long tube for solutions with 40 wt% glycerin and less, small droplets were produced; however, with the 24.5 cm long tube, the formation of the main droplet could not be prevented. By setting the pulse width to 5 ms, beside small droplets, a large droplet emerged as well. It was predicted that reducing the pulse width, which consequently decreases the first peak pressure, will stop the formation of the main droplet, but experiments showed that both the main and small droplets were eliminated. According to the pressure variations (Fig. 13), for a pulse width of 4.95 ms, the first peak pressure is still high enough to produce the main droplet; however, the second peak pressure has slightly dropped. For smaller pulse widths, the second peak pressure decreases considerably, preventing the formation of small droplets.

**Frequency of Pressure Variations within the Droplet Generator**

The droplet generator can be modeled as a Helmholtz resonator [13,14,15] which is a container of gas (usually air) with an open hole or neck (Fig. 14). When pressure strikes the neck, air inside the neck moves back and forth and compresses the air inside the container. The corresponding oscillation frequency $F(\text{Hz})$ can be determined by

$$F = \frac{c}{2\pi} \sqrt{\frac{A}{IV}}$$

where $c$ is the speed of sound in air, $V$ is the volume of the cavity inside the droplet generator, and $A$ and $l$ are the cross sectional area and the effective length of the neck, respectively. The parameter $l$ is defined by $l = L + 0.8\sqrt{A}$ where $L$ is the length of the neck. Since only a small amount of liquid (<0.5 ml) was used during experiments, the effect of liquid volume could be neglected when calculating the frequency. This relation shows that a shorter neck produces a larger frequency than a longer neck. Experimental and theoretical values for the oscillation frequency are demonstrated in Table 4.

**Size of Droplets**

The size of droplets mainly depended on the nozzle diameter. The diameter of droplets was measured for different glycerin concentrations, supply pressures, and nozzle sizes using the image analysis software. Since the supply pressure had no significant effect on the mean diameter of droplets when a 204 µm diameter nozzle was used, the corresponding droplet size range and mean diameters were obtained regardless of the used supply pressure (Table 5). The results show that for a mixture with 55 wt% glycerin, the diameter is 71-80% the nozzle diameter and this range is 65-79% the nozzle diameter for 85 wt% glycerin.

For a 102 µm diameter nozzle, the supply pressure was set to 207 kPa (30 psig). Table 6 shows the droplet size range and mean diameters when single droplets were produced from mixtures with different concentrations, except water, for which multiple droplets were produced. The diameter range of single droplets, regardless of glycerin concentration, was 1 to 1.4 times the nozzle diameter when a 12 cm long tube was used. For the same experimental setup, but a 24.5 cm long tube, the diameter ranged from 0.73-1.45 times the nozzle diameter.

**Effect of the Nozzle Shape on the Size of Droplets**

By comparing the droplet size range for the 102 and 204 µm diameter nozzles, although smaller droplets were produced from the smaller nozzle, the reduction of the droplet diameter was not as much as expected. One possible reason could be the nozzle profile. An ideal nozzle would have a tapered cross section ending up in a short cylindrical hole with an aspect ratio of about one-to-one (Fig. 4) [1]. Nozzles with conical cross sections were found to be able to work at low ejection pressures, while also not ingesting air bubbles into the hole during droplet generation. High aspect ratio straight cylindrical holes may have high resistance to liquid flow, which prevents droplet ejection at reasonable pressure pulse levels. As shown in Table 1, 51 and 102 µm diameter nozzles may have larger aspect ratios than a 204 µm diameter nozzle, having a higher resistance to liquid flow. Therefore, a higher pressure will be required to ejection a droplet, which can cause more liquid accumulation right at the nozzle exit.

**Summary and Conclusions**

A pneumatic droplet generator to produce droplets smaller than the nozzle diameter was described and the effect of various experimental parameters was discussed. The required pressure variation to generate these droplets was created within the droplet generator using 12 and 24.5 cm long exit vent tubes and small droplets were produced during the second peak pressure. Experiments were carried out using water/glycerin mixtures with different concentrations and the droplet
formation was significantly affected by viscosity. Depending on the nozzle size, small droplets could not be generated when the viscosity was too low or too high. For low viscous liquids, small droplets could be obtained only when a small nozzle (102 \(\mu\)m in diameter) was used and for high viscosities a larger nozzle (204 \(\mu\)m in diameter) was required resulting in different ranges for the Ohnesorge number. Another parameter that affected the range of the Ohnesorge number was the tube length at the exit vent. By using a longer tube small droplets could be generated from high viscous liquids.

Comparing the Ohnesorge number range obtained by Chen and Basaran [4] (0.1-0.2 for solutions with 50-61 wt% glycerin) with our results (0.21-1.73 for solutions with 70-90 wt% glycerin and a nozzle diameter of 204 \(\mu\)m; 0.015-0.15 for solutions with 0-60 wt% glycerin and a nozzle diameter of 102 \(\mu\)m), it can be concluded that the applied technique may also affect the droplet formation and Ohnesorge number range. It would be possible to produce small droplets from other liquids by using this system, provided that the Ohnesorge number lie in the specified Ohnesorge number range of the corresponding experimental setup.

Considering the range of droplet diameters obtained from 204 and 102 \(\mu\)m diameter nozzles, which were 0.65-0.8 and 0.73-1.45 times the nozzle diameter, respectively, it can be concluded that the droplet size is strongly affected by the aspect ratio of the nozzle. Since smaller nozzles may have a higher resistance to liquid flow which can cause liquid accumulation right at the nozzle exit, droplets larger than the nozzle diameter may be produced.

References
Figure 1. Formation of a small droplet

Figure 2. Photograph of the experimental system

Figure 3. Schematic diagram of the experimental apparatus
Figure 4. Ejection nozzle cross section with an aspect ratio of b/a

Figure 5. Schematic of the droplet generator assembly

Figure 6. Effect of a 24.5 cm long vent tube on pressure variation inside the droplet generator, Nozzle diameter: 51 µm; Supply pressure: 103.5 kPa (15 psig); Pulse width: 8.815 ms

Figure 7. Pressure variation within the droplet generator when a main droplet and irregularly sputtering droplets emerge from the nozzle

Figure 8. Single small droplet followed by a primary drop is ejected from a 204 µm diameter nozzle, Liquid: mixture with 55 wt% glycerin

Figure 9. Pressure variations within the generator when primary and small droplets were ejected, Nozzle diameter: 204 µm, Liquid: mixture with 55 wt% glycerin
Figure 10. Single small droplet emerging from a 204 μm diameter nozzle, Liquid: mixture with 85 wt% glycerin

Figure 11. Pressure variations within the generator when single droplets were ejected, Nozzle diameter: 204 μm, Liquid: mixture with 85 wt% glycerin

Figure 12. Emerging single small droplet from a 204 μm diameter nozzle at a larger pulse width, Liquid: mixture with 85 wt% glycerin

Figure 13. Pressure variations within the droplet generator for two different tube lengths when using a mixture with 40 wt% glycerin

Table 1. Dimensions and aspect ratio of different nozzle sizes
Table 2. Liquid properties at 25°C [12], and Oh numbers when using a 204 μm diameter nozzle

<table>
<thead>
<tr>
<th>Glycerin wt%</th>
<th>Density (kg/m³)</th>
<th>Viscosity (kg/m·s)</th>
<th>Surface Tension (kg/s²)</th>
<th>Oh</th>
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<tr>
<td>70</td>
<td>1180</td>
<td>0.0185</td>
<td>0.0665</td>
<td>0.21</td>
</tr>
<tr>
<td>80</td>
<td>1210</td>
<td>0.0558</td>
<td>0.0657</td>
<td>0.62</td>
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<tr>
<td>90</td>
<td>1230</td>
<td>0.1556</td>
<td>0.0645</td>
<td>1.73</td>
</tr>
</tbody>
</table>

Table 3. Liquid properties at 25°C [12], and Oh numbers when using a 102 μm diameter nozzle

<table>
<thead>
<tr>
<th>Glycerin wt%</th>
<th>Density (kg/m³)</th>
<th>Viscosity (kg/m·s)</th>
<th>Surface Tension (kg/s²)</th>
<th>Oh</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>990</td>
<td>0.00089</td>
<td>0.072</td>
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<td>1020</td>
<td>0.00109</td>
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<td>1050</td>
<td>0.00154</td>
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<tr>
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<td>1150</td>
<td>0.00938</td>
<td>0.0669</td>
<td>0.15</td>
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</table>

Table 4. Oscillation frequency within the droplet generator for two different tube lengths

<table>
<thead>
<tr>
<th>Exit Vent Tube Length (cm)</th>
<th>Frequency (Hz)</th>
<th>Error (Hz)</th>
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<tbody>
<tr>
<td></td>
<td>Experiment</td>
<td>Theory</td>
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<tr>
<td>12</td>
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<tr>
<td>24.5</td>
<td>151.6</td>
<td>151.3</td>
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</table>

Table 5. Statistics on the diameter of small droplets, produced from a 204 μm diameter nozzle and using a 24.5 cm long vent tube

<table>
<thead>
<tr>
<th>Glycerin wt%</th>
<th>Diameter Range (μm)</th>
<th>Mean Diameter (μm)</th>
<th>Standard Deviation (μm)</th>
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</thead>
<tbody>
<tr>
<td>55</td>
<td>144-163</td>
<td>153</td>
<td>6</td>
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<tr>
<td>85</td>
<td>132-161</td>
<td>147</td>
<td>6</td>
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Table 6. Statistics on the diameter of small droplets, produced from a 102 μm diameter nozzle

<table>
<thead>
<tr>
<th>Glycerin wt%</th>
<th>Tube Length (cm)</th>
<th>Diameter Range (μm)</th>
<th>Mean Diameter (μm)</th>
<th>Standard Deviation (μm)</th>
</tr>
</thead>
<tbody>
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<td>10</td>
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<td>110-136</td>
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<tr>
<td>30</td>
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