Undergraduate Research Journal at UCCS
Volume 2.2, July 2009

On-Demand Liquid Droplet Generation

Barry Cornella, Sean Hammerland, and Shawn Laabs
Dept. of Mechanical and Aerospace Engineering, University of Colorado at Colorado Springs

Abstract

The objective of this design project was to develop a working on demand droplet generator for use in ambient conditions as well as in a vacuum environment. The primary design parameters set by this project include the droplet size, speed, and consistency as well as the overall generator size and cost. Several different concept designs for a generator were considered. For the purposes of this project, the use of a piezoelectric design was used and modified to fit the design specifications that were given. This design features an actuating piezoelectric disk that deflects with voltage potential. This deflection drives the droplet generator system. By adjusting the size of the sapphire nozzle diameter and regulating the voltage and pulse width, it is possible to vary the initial velocity and size of the droplets produced. Initial testing in atmospheric condition proved successful. The generator produced an average droplet size of 1.57 mm with a percent standard deviation of 4.15% (through 15 drops). However, testing in vacuum down to 10-6 torr gave way to a problem of air out-gassing in vacuum. Small, trapped air pockets from the priming process began to rapidly expand in the generator, explosively forcing the fluid out of the generator. It was found that the primary issue was in the priming process of the generator. Several different approaches were taken to solve this problem. The out-gassing problem has proven to be a substantial technical challenge in this project and due to time constraints no current solution exists. However, there is no fundamental reason the design proposed in this project cannot work and future work will be done to alleviate these out-gassing issues.

Nomenclature

α = surface tension [N/m]
g = acceleration due to gravity [m/s^2]
h = height of the fluid column [m]
ρ = density [kg/m^3]
r = radius of nozzle [m]

Introduction

Recent studies have shown the need to determine the drag of liquid droplets at altitudes from sea level to low earth orbit (LEO). The pressure at LEO can range from 10-8 to 10-11 torr. Therefore physical experiments are necessary to measure the drag on liquid droplets for a wide background pressure range. The purpose of this project was to develop a mechanism to produce a single droplet of a specified fluid in order to measure these drag characteristics. The droplet generator must be able to operate through a range of surrounding pressures from ambient to a high vacuum environment. The goal was to produce a droplet generator capable of delivering droplets on demand with uniform size and variable speed. The material and labor costs for this project were not to exceed $5,000. The design team was to produce a working prototype of the generator at the completion of the project.

Problem Specifications and Constraints

The droplet generator design was required to meet several specifications as well as adhere to several design constraints. Aside from being an on-demand system, the droplet generator had to produce droplets within a specified droplet size, uniformity, speed, and temperature range. Other constraints included the operating pressure range, the size of the generator, the complexity and cost. The following table shows the design parameters for the proposed system.

Table 1: Design Parameters

Design Parameter	Value
Droplet Diameter Range (mm)	0.20 - 2.00
Droplet Speed Range (m/s)	0 - 5
Number of Drops	1
Droplet Standard Deviation (%)	5
Generator Volume Maximum (m^3)	0.25
Operating Temperature Range (°C)	0 - 100
Labor Time Maximum (hrs)	78
Total Cost ($)	$5000
Operating Pressure Range (torr)	$760 – 10^{-6}$

The generator was to operate using Dow Corning 704 diffusion pump oil. This fluid was chosen for its low vapor pressure characteristics which prevent the vaporization of the fluid in a vacuum environment. The following table shows the properties of DC 704 that were relevant in the proposed design.

Table 2: Dow Corning 704 Properties

D C 704 Property	Value
Vapor Pressure (torr)	3×10^{-8}
Specific Gravity	1.07
Viscosity (cSt)	39
Surface Tension (dynes/cm)	37.3

Design Concept

The design chosen for this project was based off of works from Yang et al. 1 and features a deflecting piezoelectric disk as the driving force in ejecting droplets from the generator. The design in the previously mentioned work was modified to meet the necessary specifications. Other concepts that were considered include using gas pressure as the driving force2. Pneumatic droplet generation concepts work by creating a pressure wave inside the generator by pulsing air (or other gases) through the system to eject a droplet. Other methods explored in this project included a hybrid between a pneumatic and piezo design as well as a syringe and stepper motor design. Ultimately, the piezo design was chosen for its simplicity and internal pressure controlling capabilities. Due to the low surface tension (compared to water) of the diffusion pump oil, a need for controlling the gravitational fluid pressure within the generator to prevent leakage arose. The design that best suited this need was the piezo design concept.

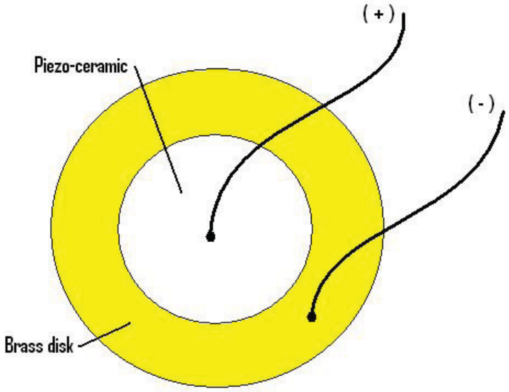


Figure 1: Piezoelectric disk

Theory

The design concept utilized in this project uses a piezoelectric disk as the driving mechanism for the droplet generator. The piezoelectric disk is comprised of a piezo-ceramic material which expands and contracts in response to a voltage potential. The piezoelectric disk was purchased from APC International and features the piezo-ceramic disk mounted on a larger brass disk. Wire leads were soldered on the brass and ceramic section as shown in Fig. 1.

When a positive voltage is applied across the leads, the ceramic expands and the disk deflects downward. Likewise, when a negative voltage is applied to the leads, the ceramic contracts causing the disk to deflect upwards. Using a Directed Energy Inc. PVX-4140 pulse generator, the voltage could be pulsed from negative to positive to obtain the maximum total deflection. The magnitude of deflection up and down is proportional to the voltage applied. The maximum voltage that this disk can endure is approximately 100 V.

By pulsing the disk from a negative voltage to a positive voltage, a thin tongue of fluid is forced out of the droplet generator through a small orifice nozzle. As the voltage switches back from positive to negative, fluid is quickly drawn back into the generator, breaking off the end of the tongue where a droplet is formed. The generator is then replenished with additional fluid from a reservoir.

Design and Setup

The piezoelectric disk forms the top of the droplet generator and was sealed by an AS568A: 025 O-ring. Figure 2 shows a diagram of the droplet generator.

The disk is clamped on the generator body (made of 6061 aluminum) with the generator cap (also aluminum) using four 8-32 x ½" bolts. Fluid is ejected through a Teflon nozzle carrier that is attached to the generator body using a Swagelok ¼ inch NPT fitting. A 0.051

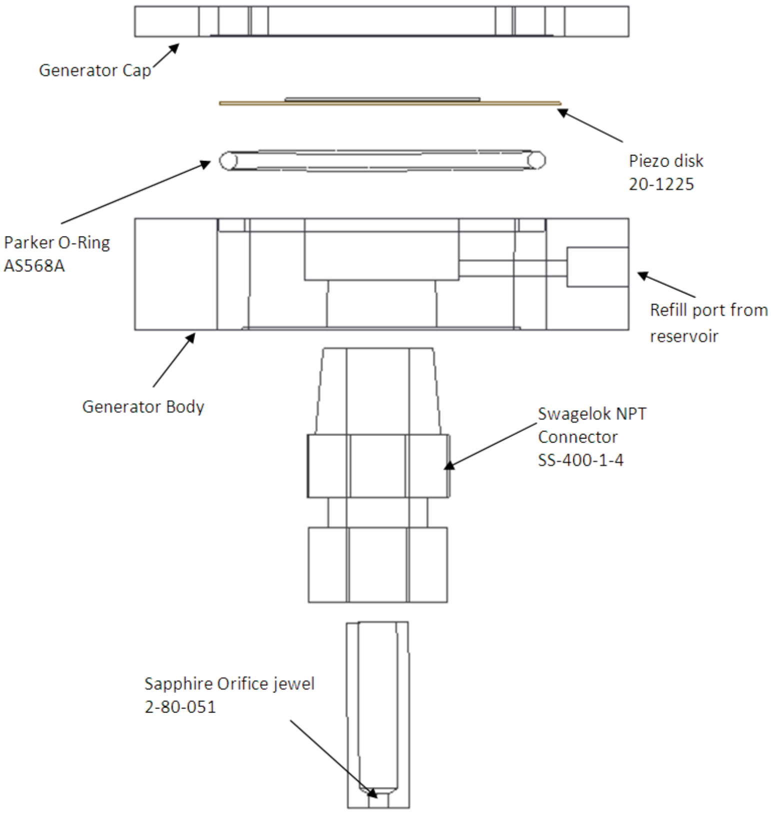


Figure 2: Droplet Generator

inch sapphire nozzle from Swiss Jewel Company (2-80-051) was pressed into the nozzle carrier. Once a droplet is ejected, the generator is refilled from the reservoir through the refill port.

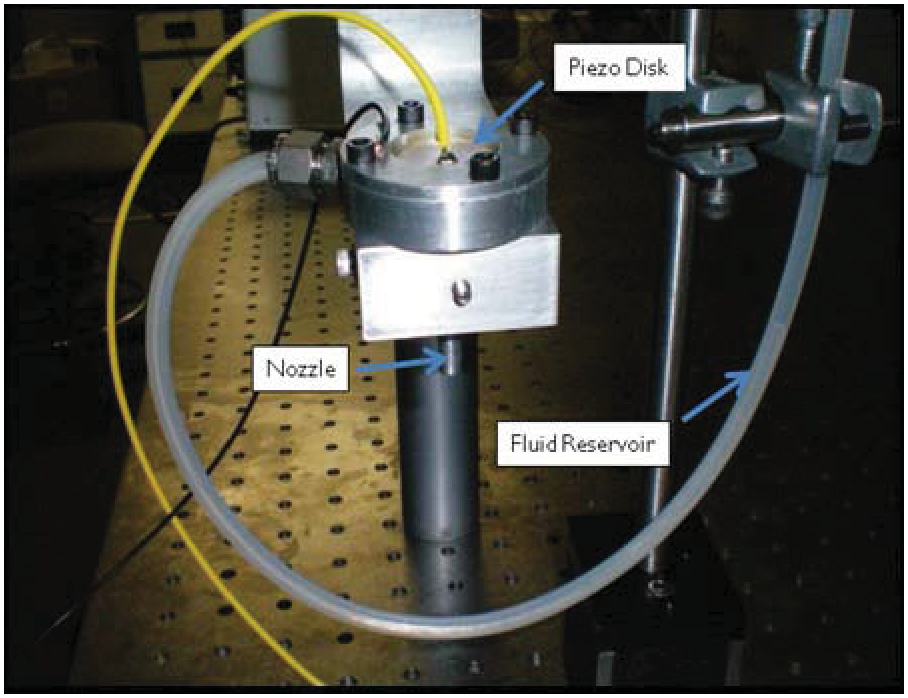


Figure 3: Droplet generator with reservoir

The reservoir for this design is comprised of a long section of flexible tygon tubing filled with DC 704. Flexible tubing was chosen specifically to enable reservoir height adjustment. By varying the height of the reservoir, the overall gravitational pressure could be controlled to prevent leaking out of the nozzle. The overall height of the fluid column that would break the surface tension of the fluid (thus cause leaking) is estimated by setting the surface tension and gravitational forces equal and solving for

$$h: h = \frac{2\sigma}{\rho g r} \qquad (1)$$

where σ is the surface tension (0.0373 N/m), ρ is the density (1065.4 kg/m3), g is acceleration of gravity (9.796 m/s2), and r is the radius of the nozzle (0.647 mm). The calculated height value was 10.8 mm. This is significantly less than the column height from the nozzle to the top of the generator (approximately 52 mm). Therefore, the reservoir fluid level height had to lie somewhere below the top of the generator. Figure 3 shows the generator and reservoir setup.

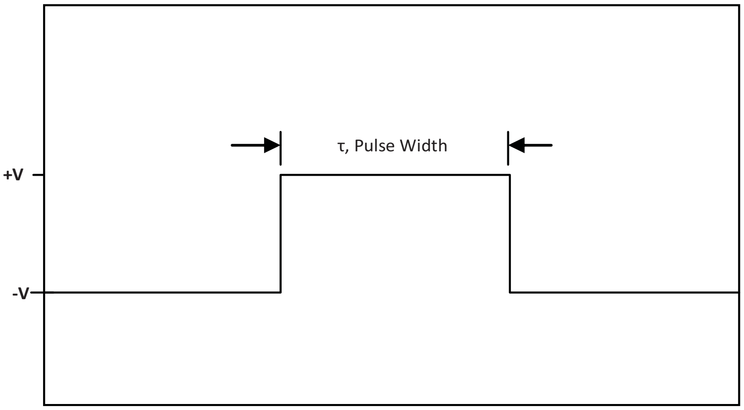


Figure 4: DEI output signal

In practice, the fluid level was simply adjusted until the bottom meniscus of the fluid was barely visible. The generator is primed simply by turning the generator upside down and drawing in the fluid through the refill port. The fluid is gravitationally fed through the reservoir tube until the fluid level reaches the nozzle surface. The generator is then quickly flipped back to its upright position depicted in Fig. 3 with the reservoir height above the bottom of the nozzle. Fluid then is allowed to drip out of the nozzle until the reservoir height drops enough to reach the equilibrium point. The nozzle is then wiped clean and the reservoir height minutely adjusted so the meniscus is slightly visible.

The generator is then mounted in a designated position inside the vacuum chamber to collect data. Leads were then connected to the piezo disk and fed to the output connection on the DEI pulse generator and ground. The DEI was powered by a positive and negative power supply connected to its inputs and was controlled using a LabVIEW VI that delivers a single TTL square wave at the designated pulse width to the DEI trigger. Once triggered, DEI delivers a square pulse to the piezo disk with the voltages ranging between the two power supply voltages (see Fig. 4). A diagram of the electrical setup is shown in Fig. 5. By varying the voltage and pulse width of the generator, the size, exit velocity, and satellites of the drop could be controlled. Further modifications to the size of the droplet can also be done by varying the orifice diameter of the sapphire jewel.

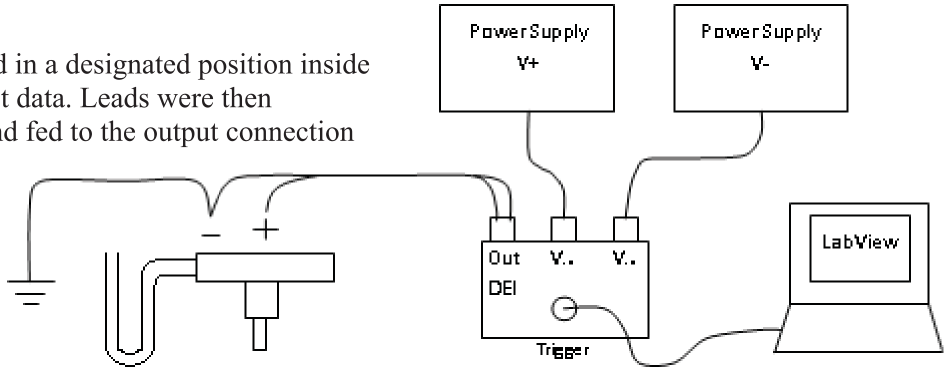


Figure 5: Electrical Experimental setup

This system easily meets all labor and budget requirements. In all, approximately one week was spent getting the generator machined, assembled and drives system set up. Excluding the electronics, the system was built for under $100 which by far meets the budget constraints.

Testing

The testing for this design occurred in two phases. First the design was tested in ambient conditions. Second, the design was tested in vacuum conditions at 10-6 torr. In both cases, the generator was mounted inside the vacuum chamber shown in Fig. 6.

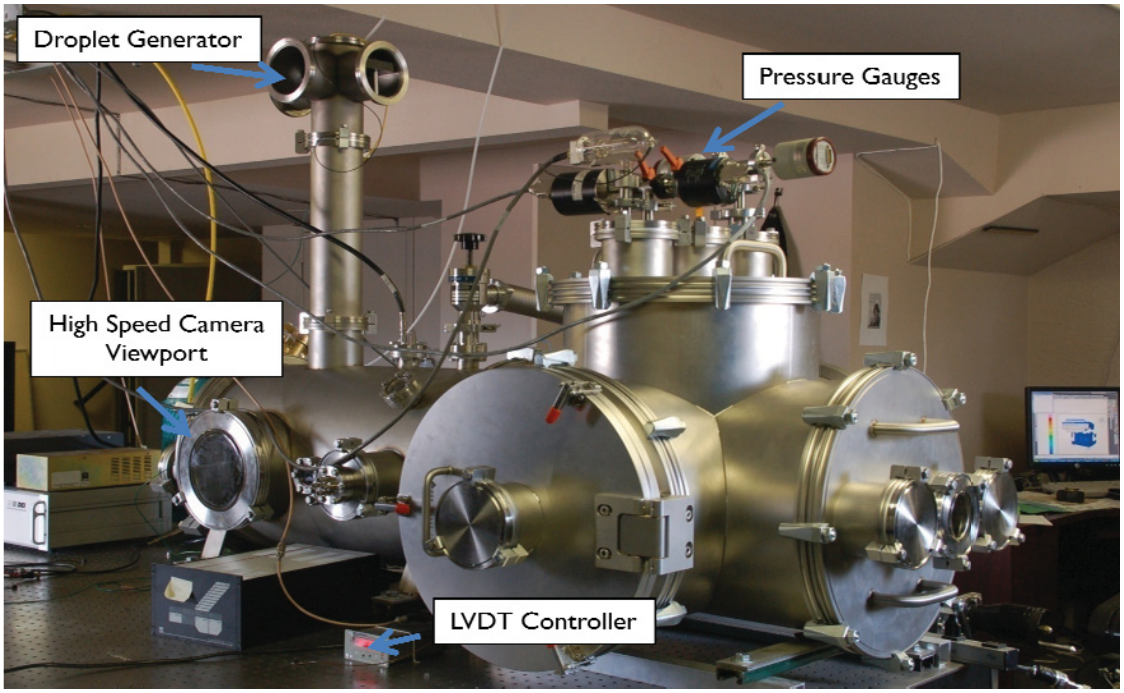


Figure 6: Vacuum Chamber

Ambient Testing

Using the setup explained above, the generator was mounted inside a cross flange at the highest point in the chamber as shown in Fig. 6. All flanges were sealed to minimize all outside disturbances however the chamber remained at ambient conditions. The drive circuit was set to pulse from -60 V to +55 V for 3 ms. Using an Ohaus digital scale, mass measurements were taken to gauge the consistency between drops. A total of 15 drops were ejected during the test with an average mass of 2.18 mg translating to an average diameter of 1.57 mm. The percent standard deviation between drops was calculated at 4.15%. The test was repeated for the same setup conditions using a high speed camera to verify the scale data and obtain speed results. Five drops were evaluated with an average diameter of 1.54 mm, an initial speed of 0.35 m/s at the nozzle and a final speed of 3.25 m/s at the scale. Figure 7 shows a series of photos from the high speed camera.

The high speed camera results confirmed that only one drop was produced by the system (no satellite droplets) and the scale measurements were reasonable. With these results, the piezo design meets all design constraints and specifications for atmospheric pressure. The droplets produced were consistent within the uniformity specification as well as within the size, speed, and cost requirements. The final speed of the droplet can be varied by adjusting the height of the generator.

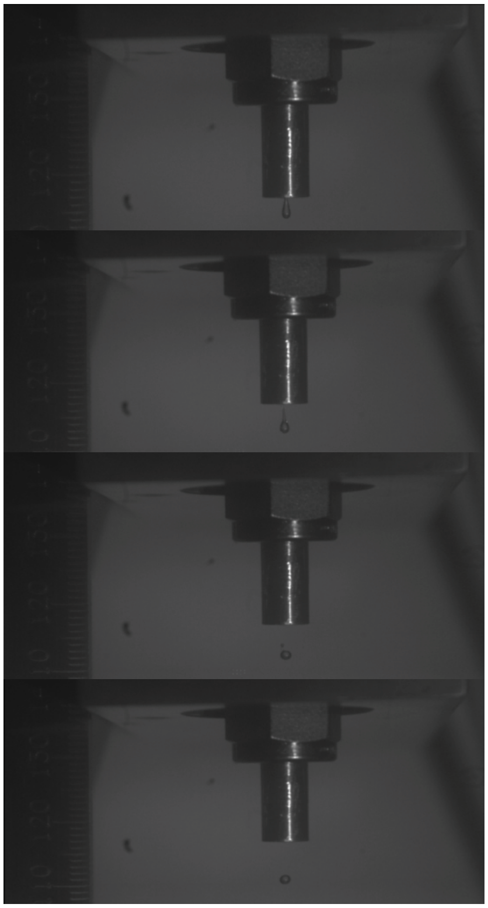


Figure 7: High speed camera results

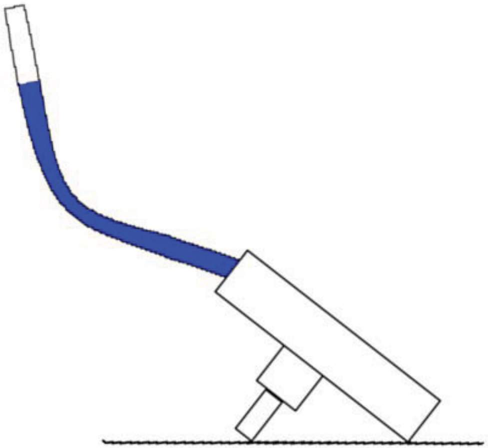
Vacuum Testing

Vacuum testing for this design followed the same setup as the ambient test. Instead of using the Ohaus scale to measure the mass consistency, a Thrust Stand Micro-mass Balance (TSMB) was used. The TSMB is a torsion balance which deflects with an applied force. A linear variable differential transformer (LVDT) measures the motion of the stand. The relationship between a steady state force (droplet weight) and its corresponding steady state deflection is linear. Therefore, to measure the consistency between the droplet masses, the consistency of the LVDT voltage from a thrust stand trace can be evaluated. LabVIEW was used to collect data from the LVDT and evaluate the deflection.

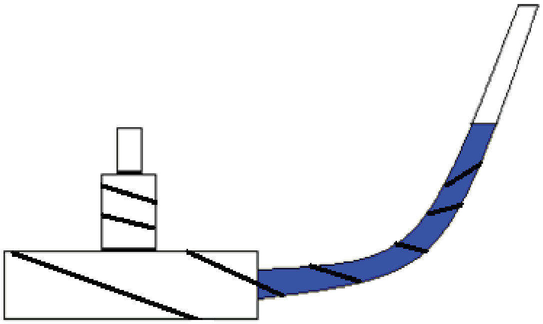
Initial vacuum testing alluded to severe issues with fluid out-gassing within the droplet generator. Small air pockets developed through the priming process began to rapidly expand inside the generator. This expansion forced the majority of the fluid out of the chamber. The ideal gas law reveals that a 1 mm air bubble at atmospheric pressure will expand to approximately 85 cm at 10-6 torr. To solve this issue, several solutions were formulated and tested.

The first solution concept was to try to better prime the system outside the chamber to eliminate any possible trapped air. The generator was again turned upside down and primed through the reservoir. In this case, fluid was drawn in at a much slower rate and the generator was agitated during the process to draw trapped air to the nozzle surface. The vacuum test was repeated and yielded the same results as the original test.

The next step was to try to provide an easier route for the air pockets to escape. A slight modification to the design was necessary for this process. An electronic latching valve was attached between the generator body and nozzle carrier. The latching valve allowed for more control over the out-gassing air by forcing it exit the generator through the reservoir. Once the generator was purged of all air, the latching valve could open and allow fluid flow through the nozzle. To ensure the air had an easy exit path out of the generator, two configurations were tested. First, the generator was tilted slightly on its side as shown in Fig. 8a. In both cases, a rope heater was wrapped around the unit to expedite the out-gassing process. During the purging process, the latching valve remained closed to prevent leaking through the nozzle.



Figures 8a (above) and 8b (below): Purging configurations



The reservoir was stretched out to allow an easy escape path for the air without forcing out the fluid. The vacuum chamber was pumped down and allowed to sit at vacuum until bubbles ceased to emerge from the generator body. The second purging configuration involved turning the generator upside down as shown in Fig. 8b. In this case, the latching valve was open to allow air escape from both the nozzle and the reservoir. Again, the generator was allowed to sit in vacuum until no bubbling was visible from the generator. The latching valve was then closed at the end of the test. Following both purge tests, the vacuum chamber was brought to atmosphere and the generator was fixed back in its upright position. The vacuum testing was then repeated. No significant improvement occurred following the purge tests as substantial bubbling occurred during the pump down process.

To investigate the exact source of the air pockets, the upside down purge test was run again. However, the piezoelectric disk was replaced by a clear Mylar disk. A mirror was placed under the generator to enable visual observations of the inside of the generator body during the pump down process. Observations indicated that the o-ring groove was the primary source for air pockets. The ensuing solutions involved attempting to prime the generator in vacuum. The first priming test involved the existing design. A diagram of this priming process is shown in Fig. 9. A solenoid valve was added just below the fluid reservoir to control the flow. During the initial pump down, the latching valve at the nozzle was open to evacuate the generator, and the solenoid valve was closed to restrict fluid flow. After the generator was allowed to sit at vacuum

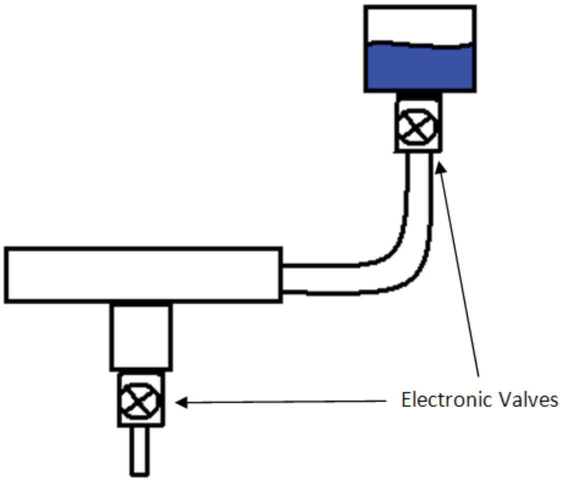


Figure 9: Priming Configuration

for approximately 90 minutes, the nozzle latching valve was shut and the solenoid valve was activated (pulsed) to allow slow flow from the reservoir to the generator. As fluid began to flow in the generator, the fluid level began to rapidly fluctuate. Eventually, fluid began to leak out of the solenoid valve and through the nozzle. The priming test was then promptly stopped.

The second priming test involved additional modifications to the generator body. A second port was added to the side of the generator to act as a relief port. A valve was attached to this port (via Swagelok) to restrict fluid flow once the generator was primed. To ensure that all the air was purged from the system, the generator body was tilted on its side and the relief port placed at the highest point of the body. In this configuration, the nozzle emerged from opposite the relief port as shown in Fig. 10. With this new design, the piezo disk operates from the side of the generator instead of the top

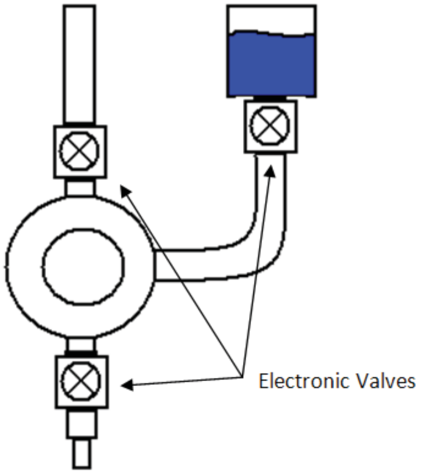


Figure 10: Modified Priming Design

The priming process was similar to the one outlined above. Both the relief valve and the nozzle latching valve were opened during the initial pump down while the reservoir solenoid valve remained closed. After approximately 90 minutes, the latching valve was closed and the fluid was once again drawn in through the solenoid valve. The relief valve remained open to allow excess air to escape during the priming process. Once the generator was primed and the fluid level above the relief valve, it could then be closed to seal off the port. However, once again the priming process was not completed. The fluid level began to rapidly fluctuate in the filling tube and the latching valve began to leak. Also, fluid began violently splashing from the relief valve, causing a substantial loss in fluid. The priming process again was promptly terminated.

Conclusions and Future Work

Although the air out-gassing still remains as the largest technical challenge for developing a droplet generator in vacuum, a working droplet generator in ambient conditions was produced. This generator meets all the specifications for atmospheric testing. Droplet size, speed, consistency, generator cost and size specifications were all easily met with this system. Moreover, there is no fundamental reason the current design cannot work in a vacuum environment provided that all air pockets inside the generator are properly purged. Additional work needs to be done to develop a proper priming process.

Ideas for a future solution include a longer pump down time to evacuate the chamber fully. Fluid may also need to be partially dispensed through the nozzle for a short duration during the priming process. This would allow the excess air to purge out of the nozzle instead of being trapped when fluid initially enters the generator. The technical challenges for this system could not be overcome within the time allotted for this project. However, there is no deep-seated reason these challenges cannot be overcome and with future work, all specifications met.

References

[1] Yang, J. C., Chien, W., King, M., Grosshandler, W. L., “A Simple Piezoelectric droplet generator,” Experiments in Fluids, Vol. 23, 1997.

[2] Cheng, S., Chandra, S., “A pneumatic droplet-on-demand generator,” Experiments in Fluids, Vol. 34, 2003.

[3] Ulmke, H., Wriedt, T., Bauckhage, K., “Piezoelectric Droplet Generator for the Calibration of Particle-Sizing Instruments,” Chemical Engineering Technology, Vol. 24, 2001.

[4] Amirzadeh Goghari, A., Chandra, S., “Producing droplets smaller than the nozzle diameter by using a pneumatic drop-on-demand droplet generator,” Experiments in Fluids, Vol. 44, 2008.

[5] Lee, E., Microdrop Generation, CRC Press, New York, 2003.