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Ultrasonic Droplet Generation of Phase Change Materials

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ABSTRACT

Droplet-on-demand (DOD) generation is a widely studied phenomenon with useful applications across many fields in engineering. While some devices incorporate thermal or electrical aspects to induce droplet ejection, this report details the use of ultrasonic waves emitted by a piezoelectric transducer. An existing experimental setup to eject and visualize droplets was modified to incorporate phase change materials, such as wax. Simulations using COMSOL Multiphysics indicated a desired frequency range of 120 kHz to 140 kHz for a liquid layer height of 4 mm to 12 mm. However, ejection ultimately occurred briefly at an operating frequency of 178 kHz. The ejected droplets ranged from 26.81 μm in diameter to 85.68 μm. The mean droplet diameter was measured to be 45.02 μm, which accurately reflected the size of the orifice (45 μm).

1 INTRODUCTION

Microdroplet generation is an applicable concept across many different fields in mechanical and biomedical engineering. Among other achievements, the development of inkjet printing in the mid-twentieth century drove advancements in the field of droplet-on-demand (DOD) generators, which incorporate the use of various technologies to achieve this feat. One common instrument used in inkjet printing is a piezoelectric device, which converts electrical pulses to strain energy in solid deformation. This deformation, occurring at a set frequency, transmits acoustic waves throughout a liquid domain, resulting in the formation of pressure fields. In acoustically actuated droplet generators, a precise region of high pressure can be created directly above an orifice, and a droplet of fluid is subsequently ejected. For example, Minov *et al.* demonstrates the use of a piezoelectric transducer to eject droplets of distilled water ranging from 134.4 μm to 461.5 μm [1].

Shan *et al.* reports the development of a DOD generator setup using a PZT piezoelectric/aluminum actuator, water as the working fluid, and a square microarray containing 169 nozzles (13 X 13 grid) [2]. The significance of this setup is the fact that many operating parameters can be dynamically adjusted (drive amplitude, frequency, height of fluid domain, etc.), allowing for real-time optimization of droplet ejection. While these studies incorporate the ejection of substances that are liquid at room temperature (such as water or methanol), few publications investigate the DOD generation of phase change materials, such as wax. Many waxes begin to melt at a temperature between 40 °C to 60 °C and form low viscosity liquids [3]. Due to the small size of the droplets, it is expected that they will solidify immediately upon ejection. The application of wax and other phase change materials in DOD generators can lead to further experiments on droplet behavior while opening additional possibilities for novel applications.

The objective of my independent study was to eject liquid candelilla wax from a microfabricated nozzle array. While a droplet size of 70 μm to 100 μm in diameter is ideal, the goal of this droplet ejection study was to achieve droplet diameters of greater than 40 μm. A large portion was spent modifying the existing setup to contain and melt the wax. This experiment was performed in the Scalable Integrated MicroSystems Laboratory under Dr. J. Mark Meacham.

2 EXPERIMENTAL METHODS

2.1 Experimental Setup Modification

The original setup consisted of a stationary platform for supporting the array, while an adjustable arm positioned above the array contained the piezoelectric material bonded to a 2 mm thick aluminum matching layer. An LED was positioned adjacent to the array to supply lighting during visualization. The microarray chosen for this device contained a 45 µm-square center orifice. Figure 1 provides an image of the experimental setup.

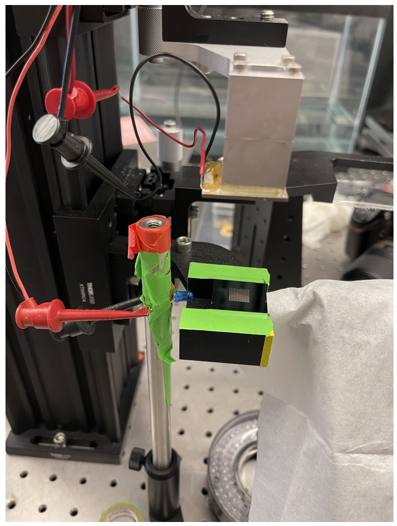


Figure 1: The original setup for DOD generation as used in Shan *et al.*

To modify the setup for experimentation with wax, I machined a pocket and through hole into an aluminum block (6" X 2 1/2" X 3/4"). The pocket and hole diameters were 2" and 5/8", respectively. The pocket depth was 5/8", allowing for a minimum fluid layer height of 1/8". An additional hole was drilled to accommodate a 3/8" diameter cartridge heater on the side of the block. Thermal paste was used to bond the cartridge heater to the aluminum. Fig. 2 is an image of the machined aluminum block, while Fig. 3 depicts the modified setup. As seen in Fig. 3, the PZT transducer is able to breach the aluminum pocket and emit acoustic waves throughout the liquid wax below. The pocket increases the surface area of the wax, allowing for uniform heating and ensuring that the arm can freely move in the vertical z-direction.

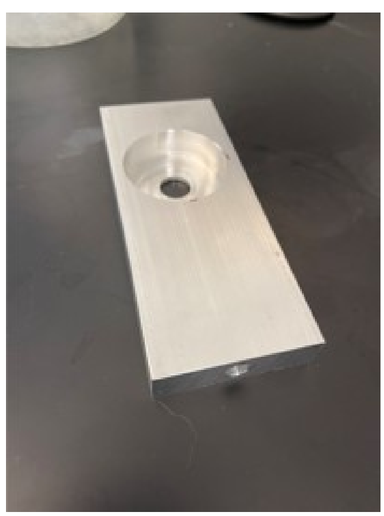


Figure 2: The machined aluminum block for containing and melting wax.

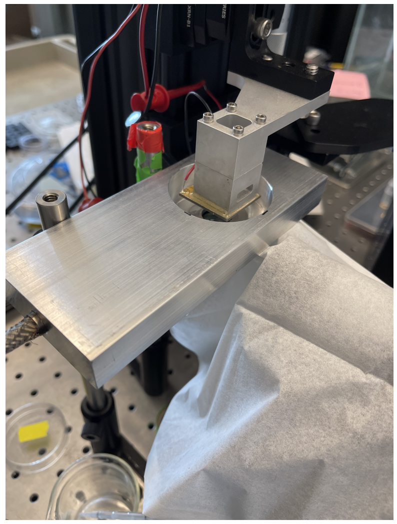


Figure 3: The modified setup for DOD generation of phase change materials.

2.2 Simulation Methods

Prior to experimentation, the acoustic wave behavior of the fluid and the thermal behavior of the heated aluminum block were simulated to gain a better understanding of the appropriate conditions necessary for droplet ejection. An existing model in COMSOL Multiphysics was run to obtain the resonant frequencies of the system for varying fluid layer heights ranging from 4 mm to 12 mm. High pressure regions close to the orifice indicated conditions suitable for droplet ejection. A CAD model of the aluminum block was created in SolidWorks 2020, and thermal simulations were run in order to gain insight on its temperature uniformity over time. Varying magnitudes of heat flux were applied to the inner surfaces of the cartridge heater hole and the temperature of the block was plotted as a function of time. Two nodes on opposite ends in the aluminum pocket were selected for analysis against one another, as seen in Fig. 4.

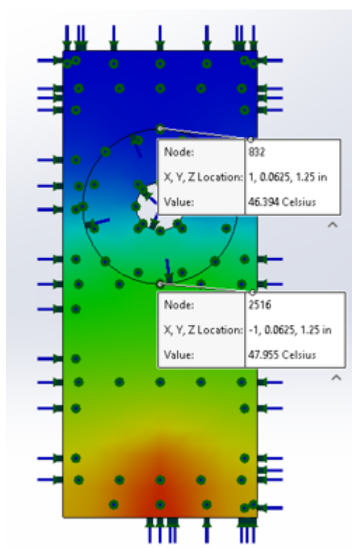


Figure 4: A schematic of the simulated block with two labeled nodes.

2.3 Experimental Procedure

To test the device, the microarray was bonded to the aluminum block with high temperature electrical tape. Candelilla wax was chosen for cleanup using acetone and a relatively low melting temperature (70 °C). A PID controller with an attached type K thermocouple provided heating control to the cartridge heater. After ensuring a set gap between the aluminum pocket and the piezoelectric transducer, candelilla wax was placed into the pocket. Sufficient time was provided for the wax to fully melt. A function generator and an amplifier were then used to supply an AC voltage to the PZT. The frequency and amplitude parameters were adjusted to match the expectations from the COMSOL model (300 mV_{PP} amplified to 20 V). An image of the working setup is provided in Fig. 5. Note that the PZT was raised to better observe the melted wax.

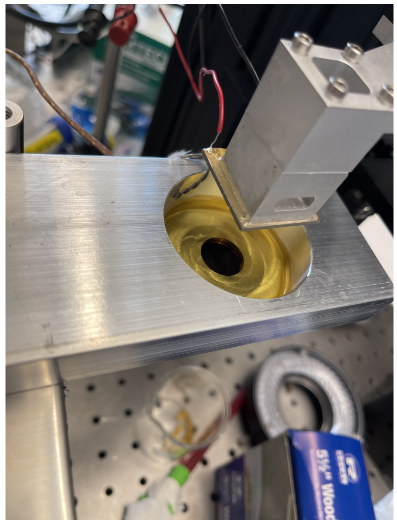
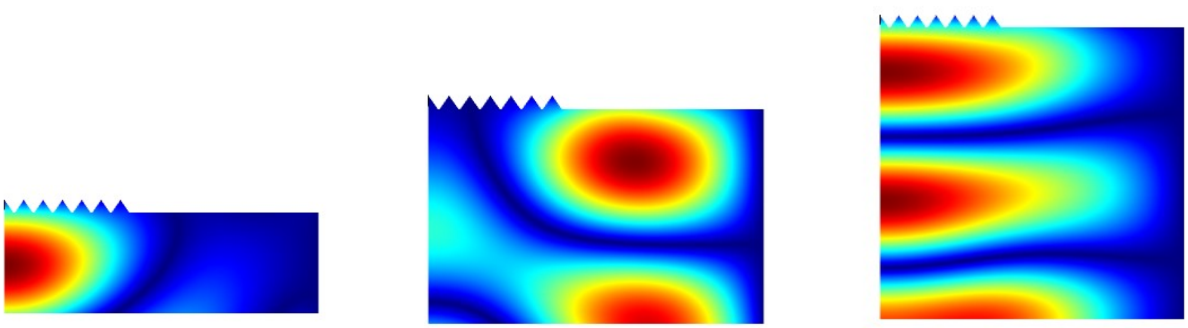


Figure 5: An image of the working setup with melted wax.

3 Results and Discussion

3.1 Simulation Results

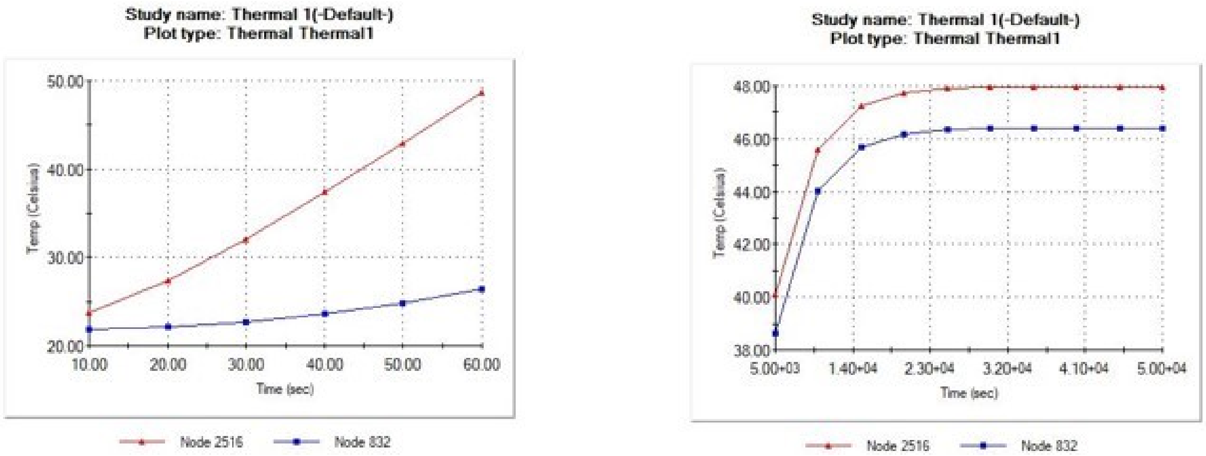
The COMSOL simulations indicated relatively consistent resonant frequencies of 120 kHz to 140 kHz across varying liquid layer heights. Fig. 6 provides a screenshot of the output for a 12 mm liquid layer height at an operating frequency of 125 kHz.



(a) **(b)** **(c)**

Figure 6: COMSOL Multiphysics output for a 125 kHz operating frequency at liquid layer heights of 4 mm (a), 8 mm (b), and 12 mm (c).

As expected, the thermal simulations of the aluminum block showed an inversely proportional relationship between heating power and temperature uniformity. The temperatures of the two nodes as a function of time for an applied heat flux of 245 $\frac{W}{in^2}$ and 6.45 $\frac{W}{in^2}$ are shown in Fig. 7.



(a) (b)

Figure 7: The results of a SolidWorks thermal study with applied heat fluxes of 245 $\frac{W}{in^2}$ (a) and 6.45 $\frac{W}{in^2}$ (b).

As seen in Fig. 7, while a high heat flux allows for rapid heating of the aluminum block within 60 seconds, the disparity in temperatures among the two nodes exceeds 20 °C. A lower heat flux ensures that the temperatures across the pocket remain within 2 °C of one another.

3.2 Droplet Ejection Results

Droplet ejection of the liquid wax was achieved at an operating frequency of 178 kHz for a brief period of time (1 s). The height of the liquid layer was roughly 5 mm. Droplet samples were collected and analyzed under a microscope, as seen in Fig. 8.

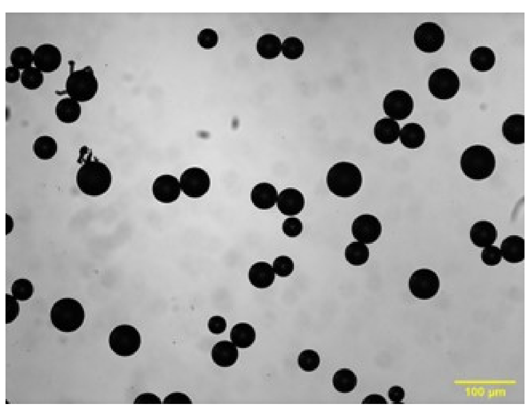


Figure 8: Microscopic image of solidified ejected droplets.

A size analysis of the droplets was performed using MATLAB. This data is presented in Table 1.

Table 1: Simple statistics of the 7 captured images of the droplets.

Image No.	Circle Count	Mean Diameter [µm]	SD [µm]	Min [µm]	Max [µm]
1	59	45.89	10.73	26.81	85.68
2	42	43.43	7.99	27.40	58.37
3	25	47.15	10.29	27.56	67.61
4	41	45.55	8.19	27.60	64.46
5	21	45.40	9.67	32.63	77.78
6	13	43.80	4.64	36.52	51.96
7	39	43.90	7.70	27.36	58.22
Mean	N/A	45.02	8.46	29.41	66.30

As seen in Table 1, the mean diameters of the droplets remain relatively consistent throughout, but the standard deviations are slightly elevated. The droplet diameters reflect the orifice size of 45 µm, as expected. A relatively small fraction (0.83%) of the droplets were in the ideal size range of 70 µm to 100 µm, yet 70.83% of the droplets were larger than the target goal of 40 µm. Larger droplets can be achieved by controlling a lower ejection frequency and by increasing the size of the orifice. While the experiment was successful, many of the droplets were still connected to one another, as depicted in Fig. 9. Further experiments are needed to determine the source and onset of these connections, as they are not desired for droplet impact studies. This could be accomplished using thermal imaging techniques, such as infrared microscopy.

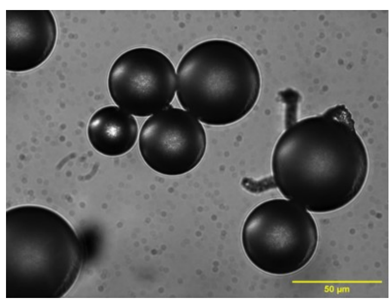


Figure 9: A microscopic image displaying the partially connected droplets.

4 Conclusion

This experiment details the process for modifying an existing DOD generator setup to accommodate phase change materials. COMSOL Multiphysics and SolidWorks simulation studies were performed in order to establish desired experimental conditions. Droplet ejection of liquid candelilla wax was successful, and the sizes of the microdroplets were measured under a microscope. While very few droplets were in the ideal size range of 70 µm to 100 µm, the majority achieved diameters exceeding the target size of 40 µm. Future studies would incorporate a form of imaging analysis to provide insight on droplet formation and connection.

I would like to thank Dr. Meacham for his continual support throughout the semester, Dr. Weisensee for her work with planning and developing the scope of the project, and the staff at the Urbauer Machine Shop at Washington University in St. Louis for their help with machining the aluminum part.

References

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