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Reducing Heat in an Acoustic Levitation System

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Abstract

An acoustic levitator is able to levitate small particles, such as pieces of Styrofoam or water, by creating standing sound waves. The levitator produces a sound wave, which is then reflected back on itself by a reflector, creating the standing waves. These standing sound waves can be observed using schlieren optics. Light from an LED point source is sent through the air between the levitator and the reflector and reflected off a mirror towards a camera. In front of the camera is a small dot on glass that blocks incoming light. If there is no disturbed air between the levitator and the reflector (no standing sound waves), the camera captures nothing, but if there is disturbed air (standing sound waves), the light is refracted by the disturbed air, misses the dot, and enters the camera, allowing the standing waves to be captured by the camera. In this experiment, the heat produced by the acoustic levitator would interfere with the capture of the standing waves as the heat waves would refract the light by a greater factor than the sound waves did. I had two objectives in this experiment; to reduce the heat in the acoustic levitator system and to observe how particles behaved when levitated by the acoustic levitator and reflected by different shapes of reflectors. I was able to significantly reduce the heat in the system by using Peltier cooling disks, while also being able to observe the behavior of pieces of Styrofoam as they were levitated by the levitator.

Introduction

Acoustic levitation is the process by which a particle is suspended in air against gravity with no physical contact due to the acoustic radiation force. The standing sound waves produced by the levitator can be captured with a camera by sending light through the disturbed air and reflected back towards the camera. Acoustic levitation was first proposed in 1933 by Bücks and Müller, and the theoretical background was derived by King in 1934[3]. Acoustic levitation has many uses. In addition to observing how small particles behave when acoustically levitated, acoustic levitators are also useful for container-less material processing, biochemical analysis, and experiments in outer space. Furthermore, acoustic levitation is used in noncontact handling methods[5], which is especially useful when dealing with the possibility of contamination or other effects that a regular container interacting with a potential sample can bring. When combined with Raman spectroscopy, acoustic levitation is also an extremely useful technique in analytical chemistry and process engineering[3].

Commented [LD1]: If you like, you could include a footnote here that refers to a light-scattering experiment on water drops:
"Generalized tertiary rainbow of slightly oblate drops: observations with laser illumination," by D. S. Langley and P. L. Marston, Applied Optics 37, pages 1520-1526 (1998).

The purpose of my experiment was to observe how Styrofoam particles behave when acoustically levitated by both flat and concave reflectors. To accomplish this, I first had to develop a system to remove heat created by the acoustic levitator. Heat waves generated by the operation of the acoustic levitator are stronger than the standing sound waves, so when the camera captured the waves between the levitator and the reflector, the heat waves would be more visible and would obscure the sound waves. The second part of my experiment was to use the implemented cooling system and the acoustic levitation system to observe and capture the behavior of the Styrofoam particles being acoustically levitated. With both a flat and a concave reflector, I observed in what areas of the standing waves the particles levitated in.

Theory

A. Acoustic Levitator

The acoustic levitator for my experiment consisted of an ultrasonic transducer and a reflector (flat and concave). The two are ideally separated by a distance equal to a multiple of half the wavelength of the acoustic waves. When the surface of the transducer vibrates (the radiator), standing acoustic waves are created between the transducer and the reflector. Due to the acoustic radiation force, small particles can be levitated by these standing waves. A flat reflector will create different levels of standing waves, while the concave reflector focuses the standing waves, creating a greater acoustic radiation force. The acoustic radiation force[3] acting on the particles is given by

$$F = -\nabla U, \tag{1}$$

where U is the acoustic radiation potential. The acoustic radiation potential[3] produced by a standing wave is given by

$$U = 2\pi R^3 \left(\frac{\overline{p^2}}{3\rho c^2} - \frac{\rho \overline{u^2}}{2} \right), \tag{2}$$

where $\overline{p^2}$ and $\overline{u^2}$ are the mean square amplitudes of the pressure field and velocity field of the air, respectively, R is the radius of the levitated particle, c is the medium sound velocity, and ρ is the air density.

The ultrasonic transducer consists of a Langevin actuator and a mechanical amplifier. The Langevin actuator consists of two piezoelectric rings, which are compressed between two cylindrical parts and are held together by a central bolt. When an electric field is applied to the piezoelectric rings, it produces a strain, causing the piezoelectric rings to oscillate. The displacement of the rings transfer energy through the amplifier and into the air above the levitator surface in the form of sound waves. The resonance frequency of the Langevin actuator depends on the length of the cylindrical parts, since it operates as a half wavelength resonator.

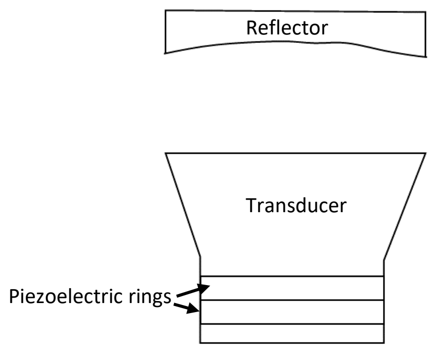


Figure 1: Diagram of the acoustic levitator used in my experiment. The function generator is connected to the piezoelectric rings, causing them to be displaced. This displacement causes the transducer to vibrate, sending acoustic waves from the transducer to the reflector.

B. Schlieren Optics

To observe the standing acoustic waves, I took advantage of the schlieren effect. The schlieren effect makes refraction of light due to changes in the index of refraction in air visible. For air, the relationship between the index of refraction, n, and the air density, ρ, is given by

$$n - 1 = k\rho, \tag{3}$$

where k is the refractivity constant, which is nearly constant over most of the visible spectrum, with its value for air being 2.3×10^{-4} m^3/kg. The expression for the angular deflection of the point light by a density gradient, $d\rho/dx$, is given by

$$\delta = kL\frac{d\rho}{dx}, \tag{4}$$

where L is the span of the disturbance in the direction of the optical axis.

To create the schlieren effect for my experiment, I used an LED point light source and sent the light towards a mirror. The light traveled roughly 232 centimeters, going through the disturbed area between the ultrasonic transducer and the reflector before hitting the mirror. After hitting the mirror, the light reflected back through the disturbed area before traveling back and entering the lens of the FlyCap camera. In front of the camera, however, is a small dot partition. The partition is positioned in such a way that if there are no standing waves between the transducer and the reflector, then the light will not be refracted and will hit the partition, allowing no light to enter the camera. If there are indeed standing waves between the transducer and the reflector, the light will be refracted, avoiding the partition and entering the lens of the camera. The experimental setup of the acoustic levitator and the schlieren optics can be seen in Figure 1.

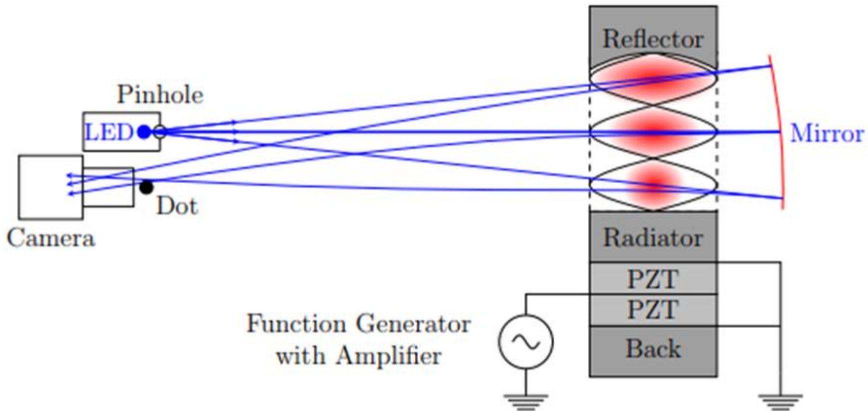


Figure 2: Experimental setup of the acoustic levitator and the schlieren optics system. The function generator supplies a voltage to the piezoelectric rings (PZT), producing a strain. The strain causes the rings to be displaced, transferring energy from the radiator to the air above it.

The brightness of the schlieren effect is proportional to the magnitude of refraction. In relation to the acoustic standing waves, the brighter the refraction appears to the camera, the stronger the acoustic radiation force is for that standing wave. Changes in air density can come from sources other than acoustic waves, however, including temperature, flow dynamics, and pressure changes. For my experiment, the presence of heat waves created by the operation of the transducer made it vital to be able to differentiate sound waves from heat waves when observing images taken by the camera.

C. Peltier Cooling Disks

As I mentioned above, the operation of the acoustic levitator produced a significant amount of heat. In order to effectively observe the sound waves produced by the levitator, it was necessary to remove excess heat from the system. In my experiment, I used a Peltier cooling disk. Peltier cooling disks are a type of thermoelectric module (TEM) that exploit the Peltier effect. By passing a current through both junctions of different metals, a temperature difference arises between the junctions. The expressions for temperature in a thermoelectric module are given by

$$T_s = T_r - \frac{k}{q}I + \frac{r}{2q}(1 + \frac{2q}{\sigma})I^2, \tag{5}$$

$$T_r = T_a + \frac{I^2 r}{\sigma}, \tag{6}$$

where T_s is the heat flow into the stage, T_r is the heat flow into the radiator, T_a is the ambient temperature, k represents the Peltier heat flow through the TEM, q represents the ordinary heat conduction through the TEM, σ represents the thermal conductance of the heat sink (radiator), I is the current passing through the TEM, and r is the resistance of the TEM.

For the Peltier cooling disk used in my experiment, the current passing through the disk caused the bottom side to heat up and the top side to cool down. To reduce heat in the levitator, I placed the levitator on a copper base (the stage for my experiment) and rested that on top of the Peltier cooling disk. I had the Peltier cooling disk resting on top of a copper container (the heat sink, or radiator, for my experiment), which was cycling water through it to help carry heat away from the system. The water was pumped through tubes from the copper container, through the pump, and into the tank. The water was then pumped out of the tank, through a chiller, and back into the copper container. A diagram of the Peltier cooling disk setup can be seen in Figure 2.

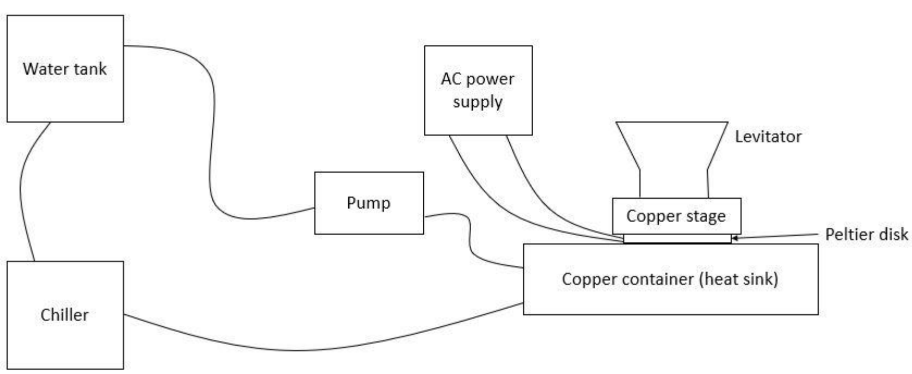


Figure 3: Experimental setup of Peltier cooling disk system in relation to the acoustic levitator. Current runs through the wires from the AC power supply, into the Peltier disk, and is grounded back at the power supply.

Experiment

A. Developing the Cooling System

Much of this experiment revolved around overcoming the problem of capturing sound waves with the camera while minimizing the presence of heat waves. At the beginning of the experiment, the apparatus consisted of the ultrasonic acoustic levitator, the lens to reflect the acoustic waves on themselves, the LED, the mirror to reflect the light from the LED, and the camera to capture the light, as seen in Figure 1. There was also a piezoelectric driver powering the levitator. The driver was controlled by a function generator, with an oscilloscope hooked up to monitor the voltages from the generator and the driver.

Initially, the levitator rested in a plastic box, where the base of the levitator was completely enclosed by plastic. While running the levitator, its temperature would routinely climb to between 35 and 40 degrees Celsius, causing a significant amount of heat wave interference where the heat from the acoustic levitator caused measurable changes in the index of refraction of the air, interfering with the measurement and capture of the sound waves. My first thought was that with the base being completely enclosed in plastic, the only place the heat waves radiating from the base of the levitator could dissipate was up out of the enclosed holder and towards the top of the levitator, where the sound waves were radiating from and causing interference. To counteract this, I thought that a holder with holes in the bottom and sides would allow the heat to dissipate away from the levitator instead of towards the top of it. To construct this holder, I used LEGO's. The different shapes and sizes allowed me to come up with a holder with a more breathable bottom while still holding the levitator firmly in place. After testing this arrangement, I found that while it decreased the temperature of the levitator, it was not enough to make a significant difference. In the LEGO holder, the temperature of the levitator would routinely be around 30 degrees Celsius, enough to cause significant heat wave interference.

Clearly the heat waves were not dissipating naturally, so I would need to implement some sort of cooling device to significantly reduce heat wave interference. The first method of cooling I tried were two 12-volt fans. I hypothesized that aiming the fans at the base of the levitator would enhance the dissipation of the heat waves. While keeping the levitator in the LEGO holder, I placed the fans 90 degrees apart and about five centimeters away from the base of the levitator. After testing this arrangement, I found that while the fans did reduce the heat of the levitator to about 25.5 to 26.5 degrees Celsius, the levitator was still not at a low enough temperature to significantly reduce heat wave interference. In addition, the added wind from the fans affected a particle's ability to be levitated.

After consulting with my advisor, we realized that water and other liquids are great conductors of heat, and that submerging the levitator completely in a liquid could take away a significant amount of heat. I researched liquids used in immersion cooling and found that mineral oil was a common one. It was not electrically conductive while still being a good conductor of heat. After creating a box for the levitator to securely rest in, my advisor and I decided that more heat could be dissipated if we pumped cool oil into the box while pumping warm oil out of it. We developed a system of plastic tubes to pump the water through the box, through a cooler, and back into the box. On the first test, however, the joints we created for the tubes were not secure enough, causing the oil to leak out of the tubes.

Deciding not to completely abandon the idea of circulating water or another liquid through the experimental setup, my advisor and I developed the current system that was used for the experimental setup. We did some research on thermoelectric Peltier cooling plates and found that combined with pumping water through a copper container, the system reduced the temperature of the levitator significantly enough to reduce heat wave interference, routinely getting the temperature of the levitator below room temperature. This allowed me to put together the cooling system seen in Figure 2.

Commented [LD2]: If you want some theory to go with the water-cooling system, I have attached an Excel sheet outlining the equations, and some of the correct numbers pertaining to the copper and the water.

B. Experimental Setup

In its final state, the experimental setup consisted of three distinct sections. The first was the ultrasonic acoustic levitator portion. This consisted of the levitator, a concave lens resting above it at a separation distance that could be adjusted to an optimal distance, and a mirror positioned just behind the levitator to reflect the LED light back towards the camera. The levitator was supplied with a current from a piezoelectric driver. The driver was hooked up to a function generator to control what kind of function the driver operated at. An oscilloscope was hooked up to both the function generator and the piezoelectric driver to monitor the voltages from both. This setup can be seen in Figure 1.

The second component was the cooling system that was developed to reduce the heat wave interference captured by the camera. This consisted of a copper stand for the levitator to rest on, which sat on top of a thermoelectric Peltier ceramic cooling plate. The plate rested on top of a hollow, copper container. Inside the container was distilled water, which was pumped from the tank, through a cooling device, into and out of the copper container, through the pump itself, and back into the tank. The cycling of cool water into the copper container combined with the cooling effect of the thermoelectric plate kept the levitator near room temperature while it was being operated. This setup can be seen in Figure 2.

The third component to the experimental setup was the LED light and the camera. The LED sent light waves towards the levitator. These light waves would go through the area between the levitator and the lens above it, reflect off the mirror, and then be detected by the camera. In front of the camera was the partition, blocking any light that was not diffracted. The partition could be adjusted to allow the optimal amount of light into the camera.

C. Calibration and Operation of Instruments

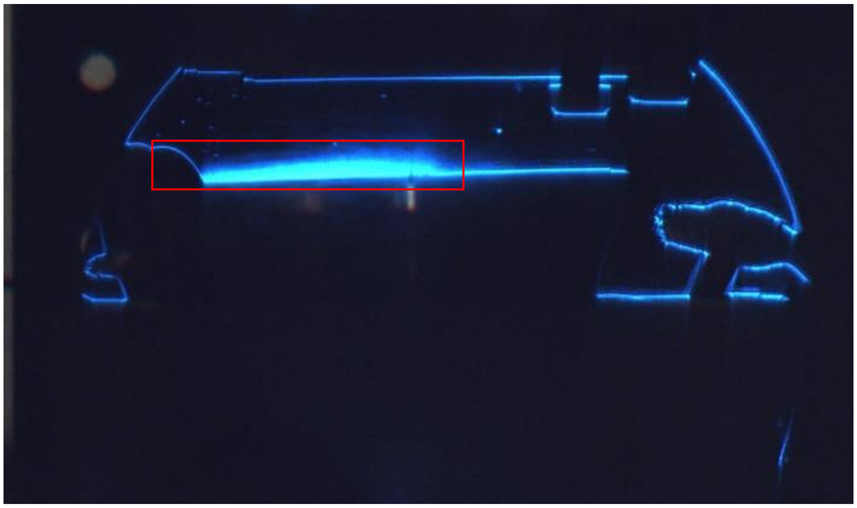
When experimenting with the ultrasonic acoustic levitator, it is necessary to keep the frequency supplied by the function generator around 25.0 ± 0.5 kHz due to the length of the parts used in the Langevin actuator. This value matches the resonance frequency of the levitator, which allows for the greatest displacement in the piezoelectric rings and therefore the greatest acoustic radiation force. Also, the function generator was supplying the same 25.0 kHz frequency to the LED sending light through the observation area. By having the acoustic waves and the light waves at the same frequency, it makes the acoustic waves more easily detectable since the pulsing LED creates a strobing effect for the acoustic waves. In addition, the peak-to-peak voltage of the function generator should be no more than two volts. This allows the piezoelectric driver to run at its maximum efficiency without overloading it.

In addition to monitoring the voltages from the function generator and the piezoelectric driver, the oscilloscope has another function. By altering the frequency on the function generator by a few Hz, the oscilloscope shows the user if the phase of the frequency coming from the function generator matches the phase of the voltage being supplied to the driver. Matching the phases between the current and the voltage ensures that the acoustic levitator is operating at its resonance frequency, creating more easily detectable acoustic waves while supplying the most levitating force to the particle between the levitator and the lens.

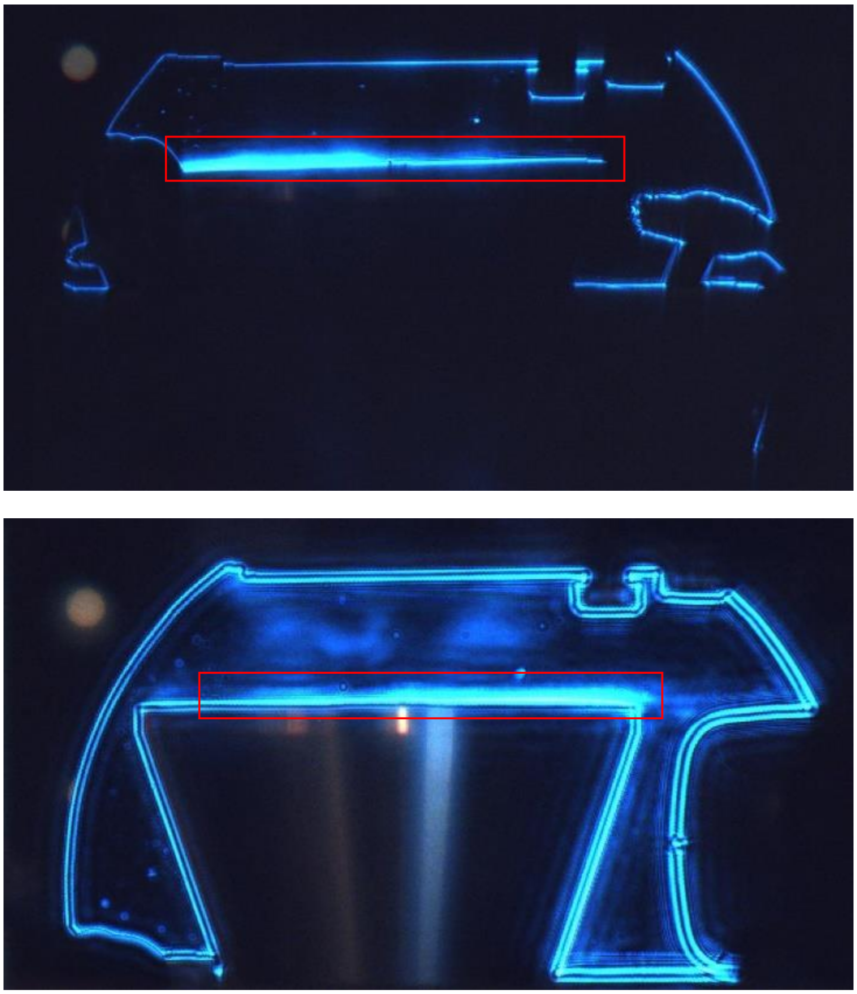
For the camera and LED system, it is imperative that the light reflected off the mirror from the LED is centered on the dot partition in front of the camera so that any diffraction due to acoustic waves in the observation area is captured by the camera. The pinhole attached to the LED has multiple different sizes, and it can be changed if the amount of light hitting the camera needs to be adjusted. In order to see the smallest of changes in the index of refraction of the air due to the acoustic waves, it is necessary to have the light from the LED centered on the dot partition so there is a stark contrast between no waves diffracting the light and sound waves diffracting the light.

D. Experimenting with the Cooling System

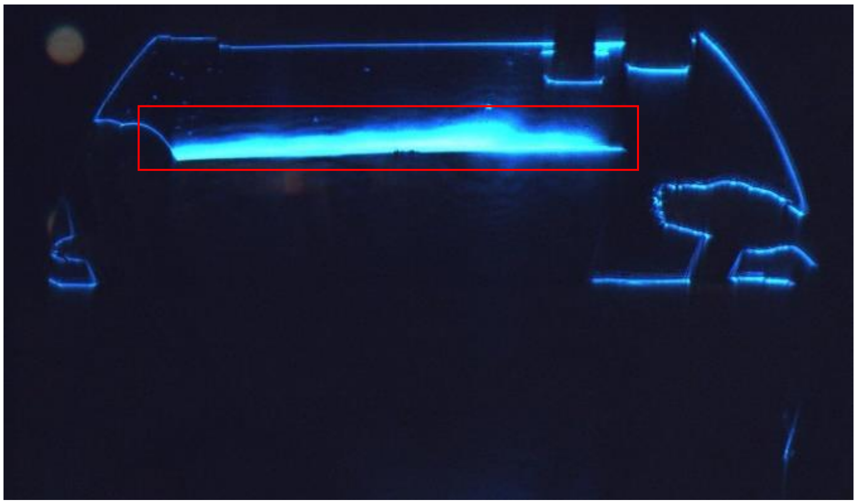
After implementing the cooling system and experimenting with the levitator, I was able to get many captures of acoustic waves with the Point Grey FlyCap FL3-U3-88S2C-C camera. The difference in heat wave interference from the original setup to the current setup was significant. Standing acoustic waves were detectable with the cooling system in place, whereas the original system had too much heat interference to detect the acoustic waves. The images that follow are comparisons of the original setup to the current system.

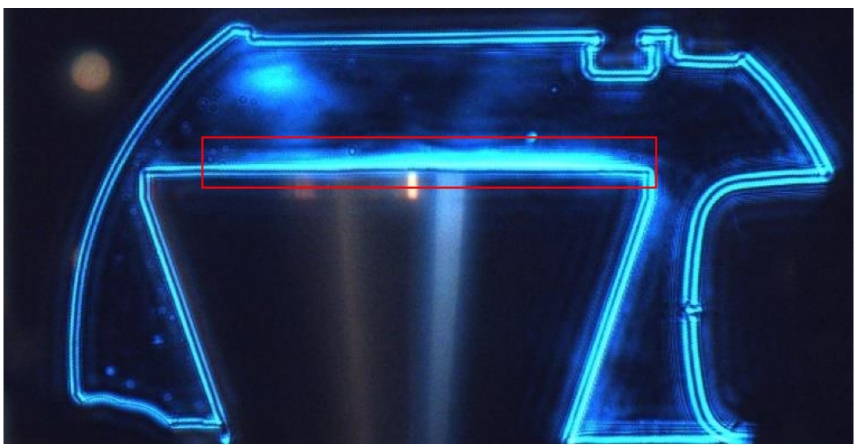


Figures 4 and 5: The levitator after 5 minutes of operation; the first image is before the cooling system was implemented and the second image is after the cooling system was implemented. The heat waves are denoted by the boxes.



Figures 6 and 7: The levitator after 10 minutes of operation; the first image is before the cooling system was implemented and the second image is after the cooling system was implemented. The heat waves are denoted by the boxes.





Figures 8 and 9: The levitator after 15 minutes of operation; the first image is before the cooling system was implemented and the second image is after the cooling system was implemented. The heat waves are denoted by the boxes.

E. Observing Sound Waves with the Concave Reflector

With the concave lens as the reflector, I was able to observe acoustic waves at two separation distances: 11.77 and 19.46 millimeters, with uncertainties of 1.0 millimeters. The acoustic waves appeared to be stronger at the 11.77 mm separation distance compared to the 19.46 mm distance. At the 11.77 mm separation distance, the high-pressure zones of the standing wave appeared to shift to the middle of the levitator when the lens was adjusted to a distance a few millimeters further from the levitator. The captures of the standing waves are seen in Figures 9, 10, and 11.

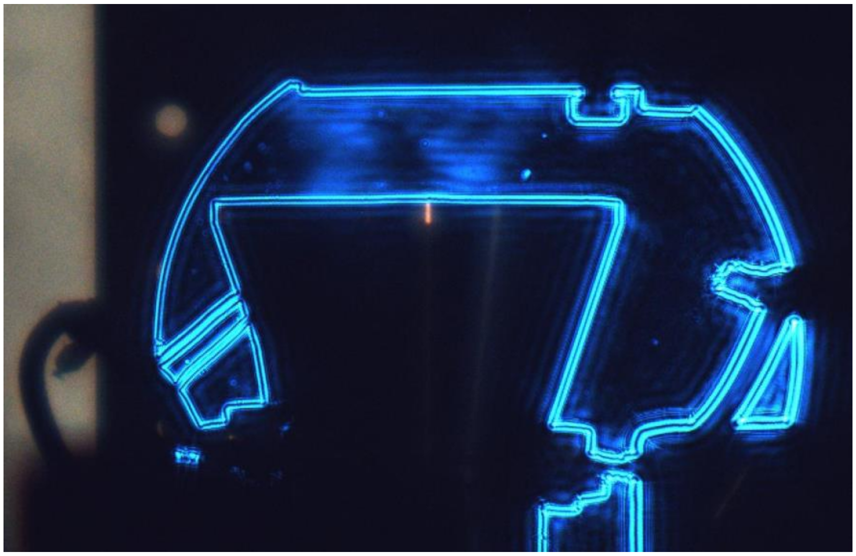


Figure 10: A picture of standing acoustic waves at a separation distance of 19.46 mm. The waves are denoted by the light blue areas between the levitator and the lens, as opposed to the black background where no waves are present.

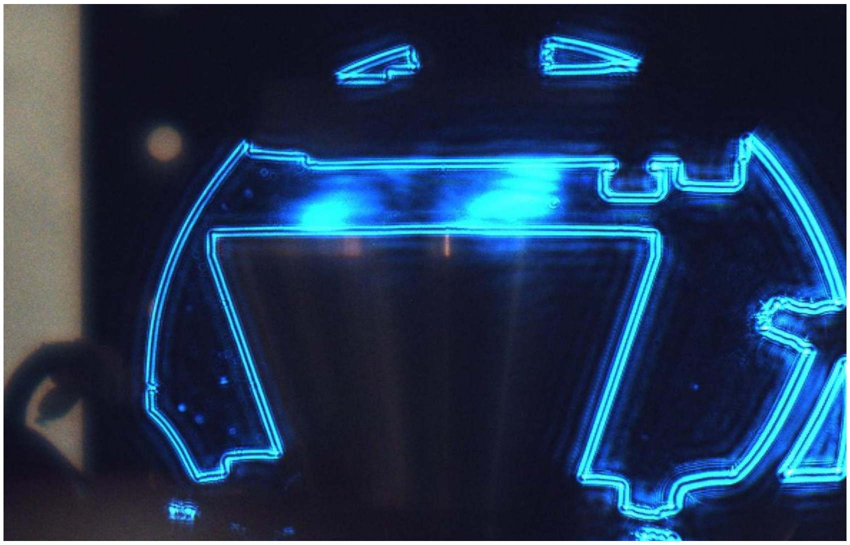


Figure 11: A picture of standing acoustic waves at a separation distance of 11.77 mm. The high-pressure zones are a brighter blue, indicating a stronger force.

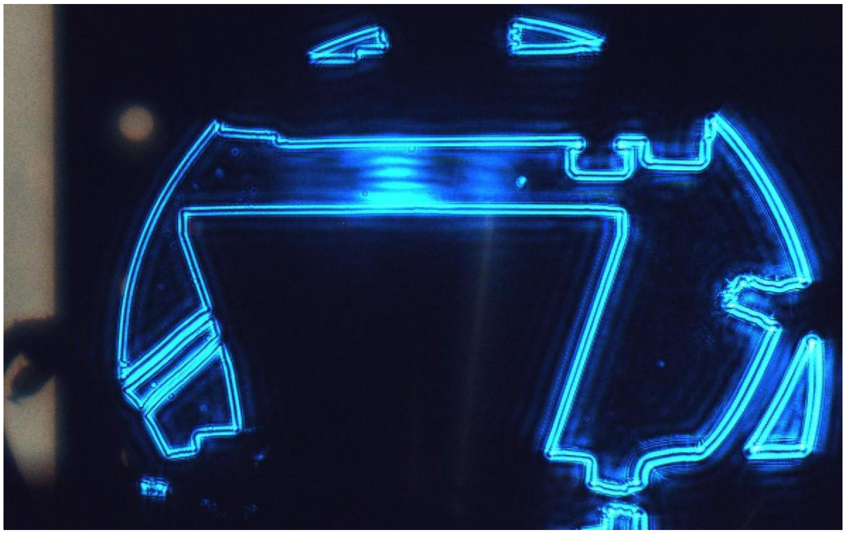


Figure 12: Adjusting the separation distance at 11.77 mm a few millimeters further from the levitator shifts the high-pressure zone to the middle of the levitator.

Observing the captures of the standing acoustic waves, the shape of the waves appears to be controlled by the concavity of the lens. A flat reflector would create standing waves that have a wide extent, while a reflector with a significant amount of concavity would create standing waves that are focused closer to a point.

When adding a particle to be levitated, I observed that the particle rests in both the high and low-pressure zones created by the standing waves. Figures 12-21 show where the particles levitate in comparison with where the standing waves are created at different separation distances.

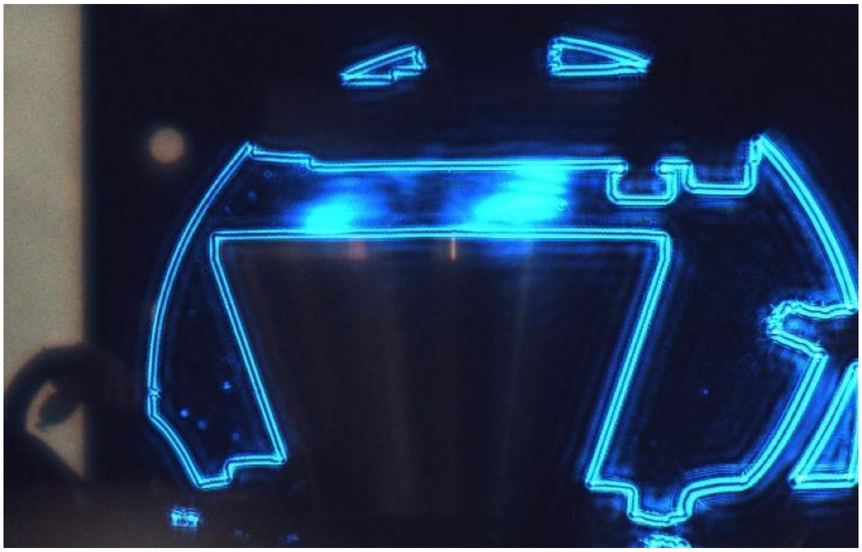
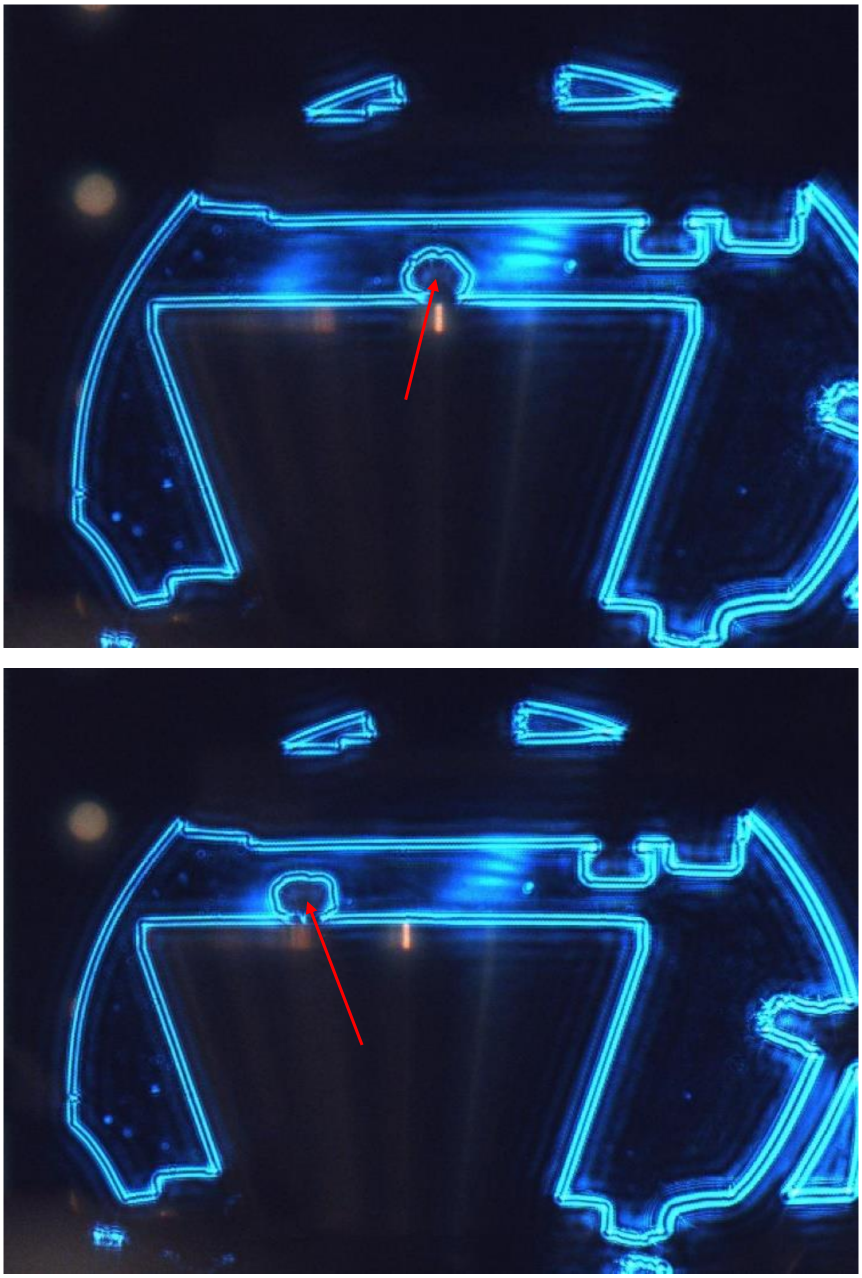


Figure 13: The standing waves created at a separation distance of 11.77 mm. The high-pressure zones are bright blue while the low-pressure zones are dark blue to black.



Figures 14 and 15: The Styrofoam particle (denoted by the arrows) is shown levitating in both the high- and low-pressure zones created by the standing waves at 11.77 mm.

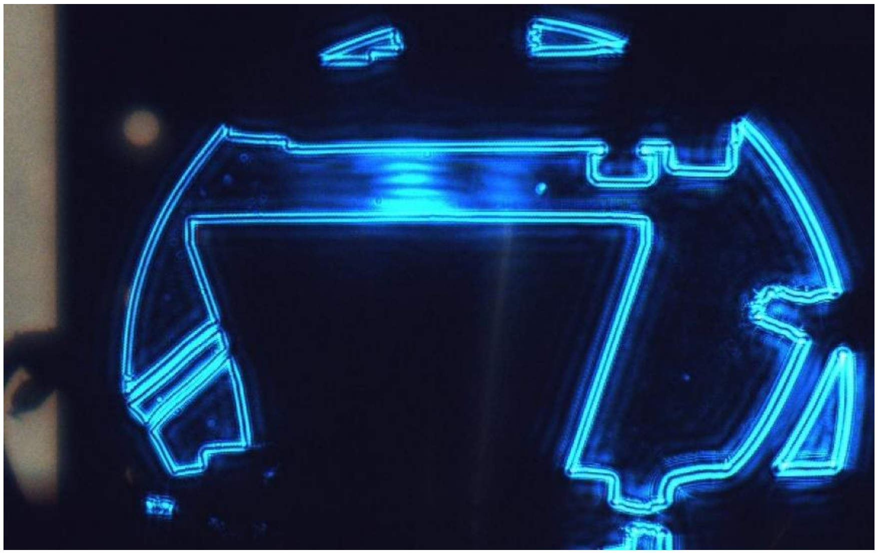
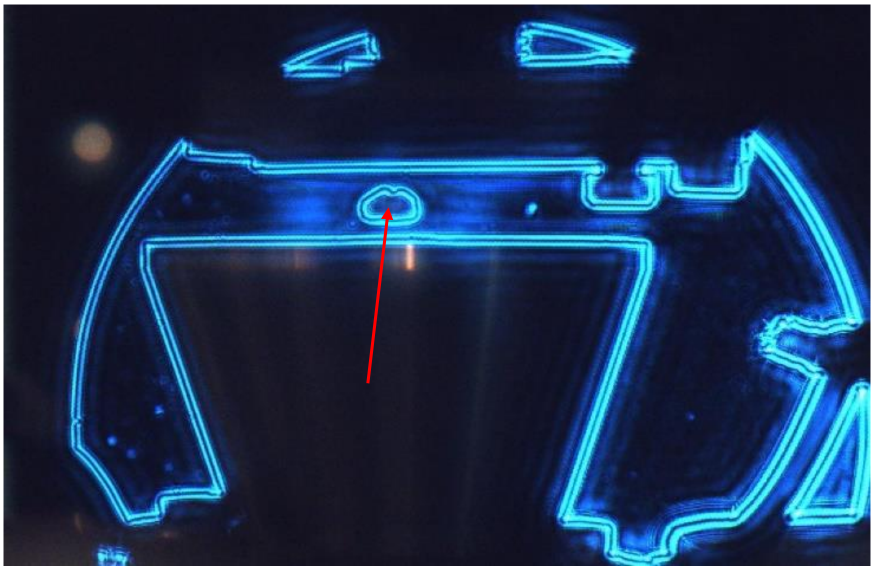
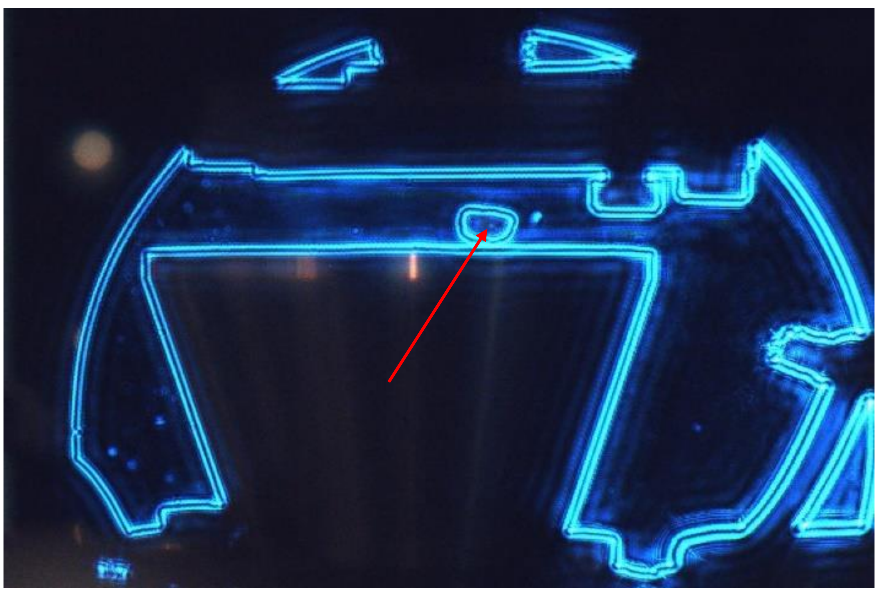


Figure 16: Shifting the standing waves towards the middle of the levitator at 11.77 mm by decreasing the separation distance by fractions of a millimeter. The high-pressure zones are bright blue while the low-pressure zones are dark blue to black.





Figures 17 and 18: When the high-pressure zones of the standing wave shift to the middle, the particle (denoted by the arrows) still levitates in both the high and low-pressure zones at 11.77 mm.

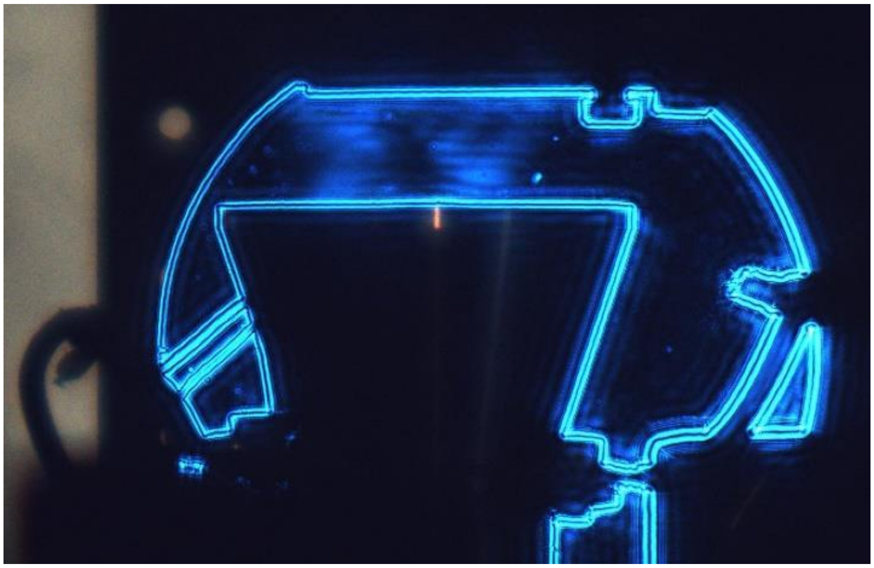
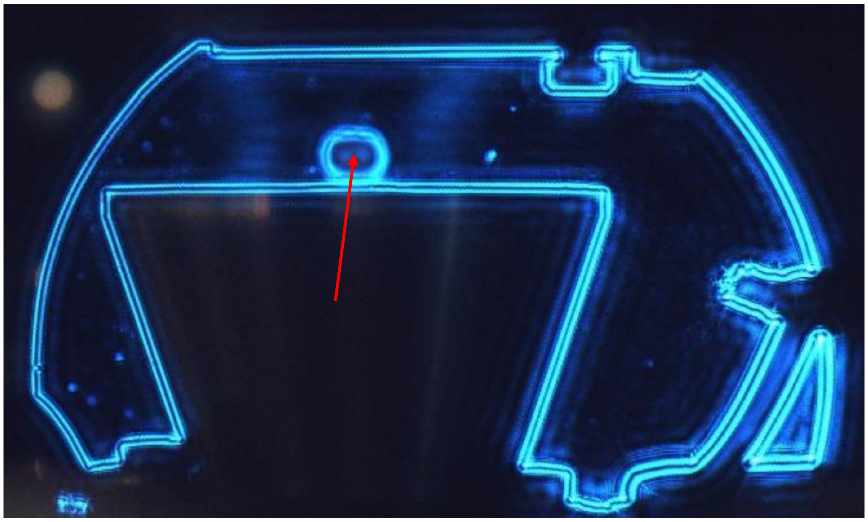
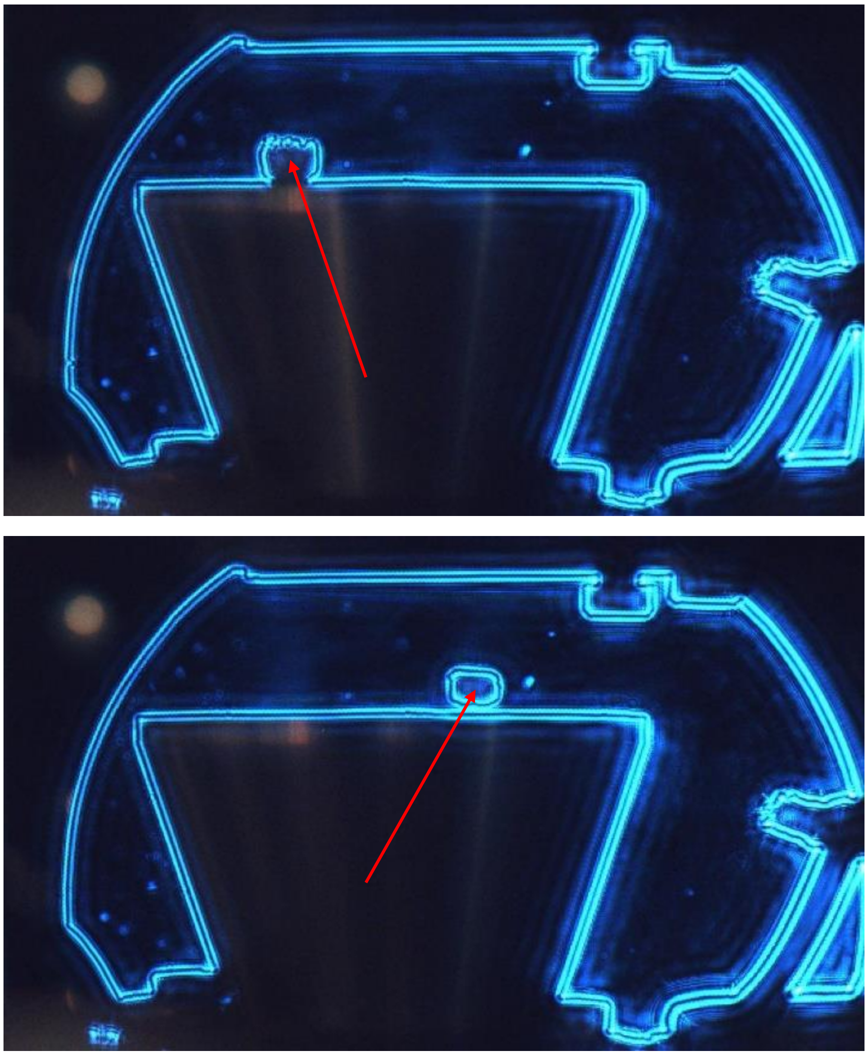


Figure 19: The standing waves created at a separation distance of 19.46 mm. The high-pressure zones are bright blue while the low-pressure zones are dark blue to black.





Figures 20-22: The Styrofoam particle (denoted by the arrows) is shown levitating in both the high and low-pressure zones at a separation distance of 19.46 mm.

I was able to levitate particles at separation distances of 26.15 mm and 31.66 mm (with an uncertainty of 1.00 mm) as well, but the standing acoustic waves were not strong enough to be picked up by the camera. Due to this, I was not able to determine if the Styrofoam particle in the following figures was being acoustically levitated in high- or low-pressure zones. At the 26.15 mm separation distance, two particles could be stably levitated.

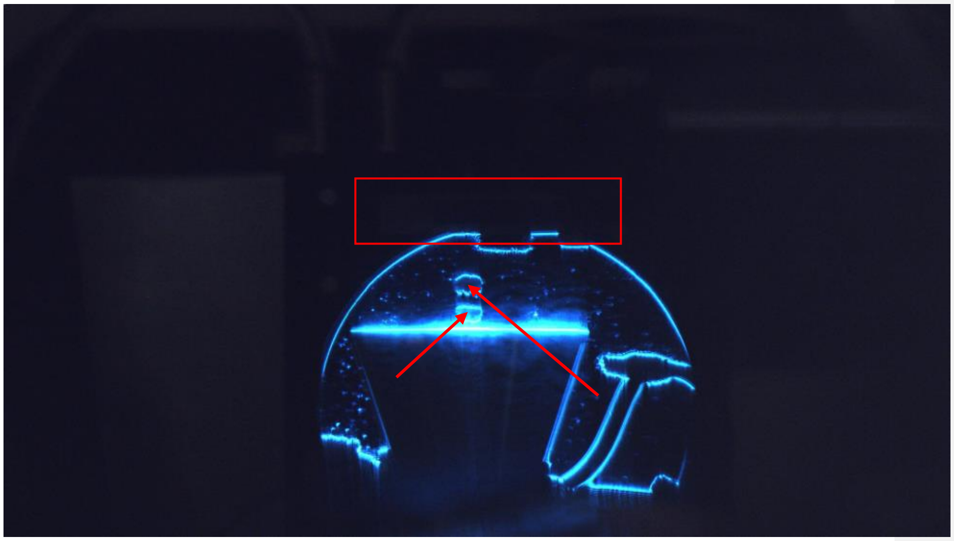


Figure 23: Two Styrofoam particles are seen levitating at the 26.15 mm separation distance. The reflector is denoted by the box and the particles are denoted by the arrows.

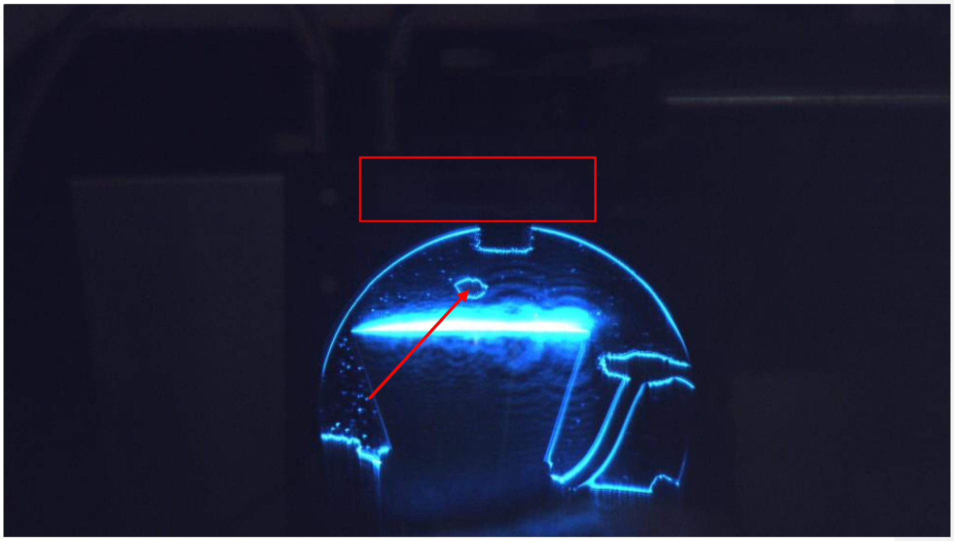


Figure 24: The Styrofoam particle is show levitating at the 31.66 mm separation distance. The particle is denoted by the arrow and the reflector is denoted by the box.

F. Observing Sound Waves with the Flat Reflector

With the flat reflector, I was able to observe acoustic waves at separation distances of 6.89, 14.11, 21.09, 28.09, and 35.00 mm, all with an uncertainty of 1.0 mm. The acoustic waves appeared to have a stronger acoustic radiation force at the 6.89 mm separation distance, with the force decreasing as the separation distance got farther apart, which can be seen from the following figures as the sound waves become dimmer at greater separation distances. The high-pressure zones appeared to stack on top of each other as the separation distances increased. At 6.89 mm there was one high-pressure zone, at 14.11 mm there was two, at 21.09 mm there was three, at 28.09 mm there was four, and at 35.00 mm there was five high-pressure zones.

Observing the shape and position of the standing acoustic waves, the shape of the waves is more defined than the ones for the concave reflector. Also, they do not extend all the way from the levitator to the reflector like the waves for the concave reflector did, but form layers on top of each other. They do not extend to the full width of the reflector and levitator either, which contradicts my prediction that a flat reflector would create wide standing waves.

When adding Styrofoam particles to be levitated, I observed that the particles only levitated in high-pressure zones. At the closer separation distances of 6.89 mm, 14.11

mm, and 21.0 mm, the particles levitated stably in the high-pressure zones. At the farther separation distances of 28.09 mm and 35.00 mm, however, the particles wavered in and out of the high-pressure zones and were not completely stable.

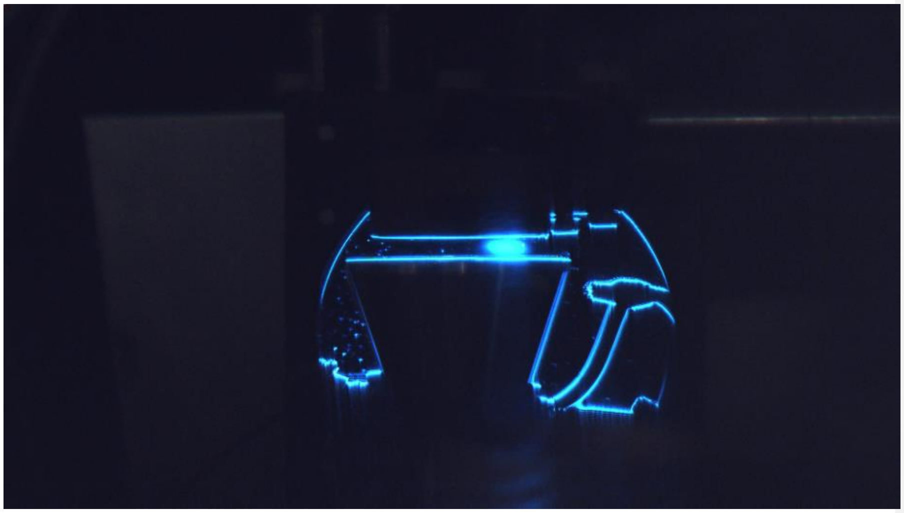


Figure 25: The acoustic standing waves created by the flat reflector at 6.89 mm. The bright blue shows that the standing wave has a strong acoustic radiation force.

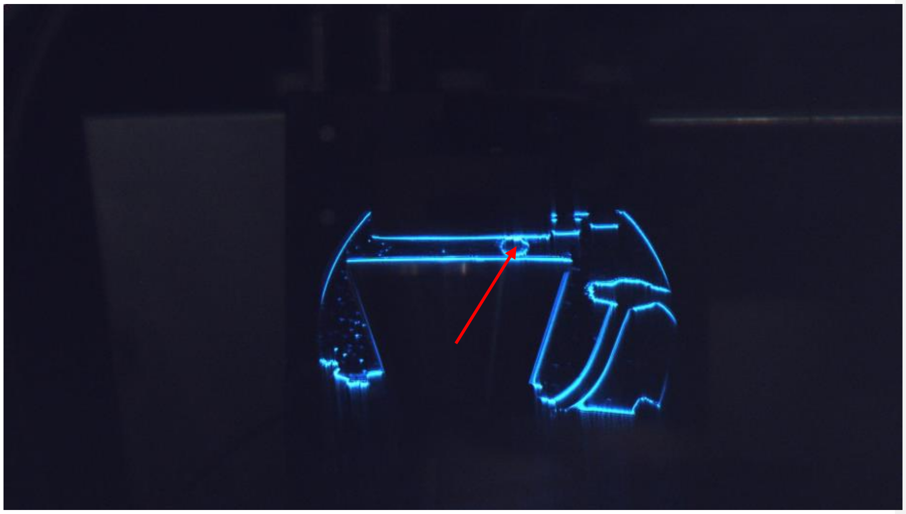


Figure 26: The Styrofoam particle levitating stably in the high-pressure zone at a separation distance of 6.89 mm. The particle is denoted by the arrow.

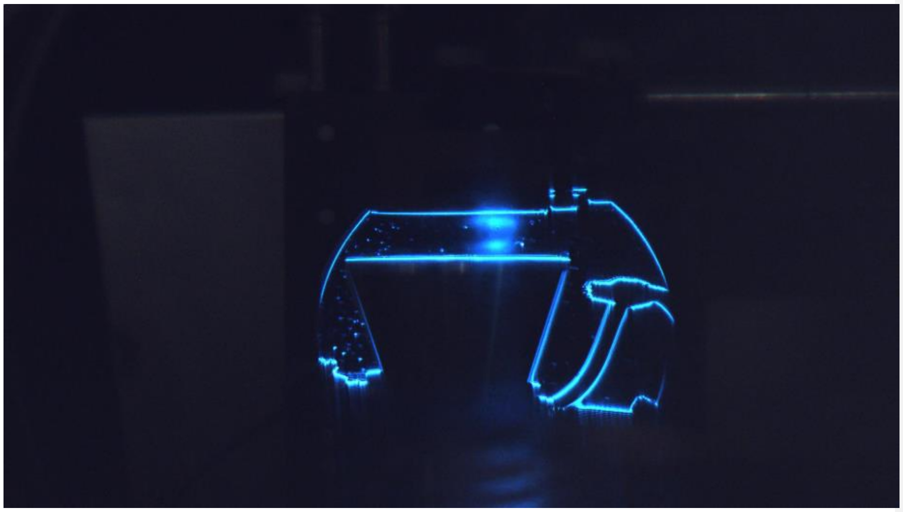


Figure 27: The acoustic standing waves created by the flat reflector at 14.11 mm. The blue is not as bright as the waves at the 6.89 mm separation distance, indicating that the waves are weaker as the separation distance increases. The waves are stacked on top of each other, creating two layers of waves.

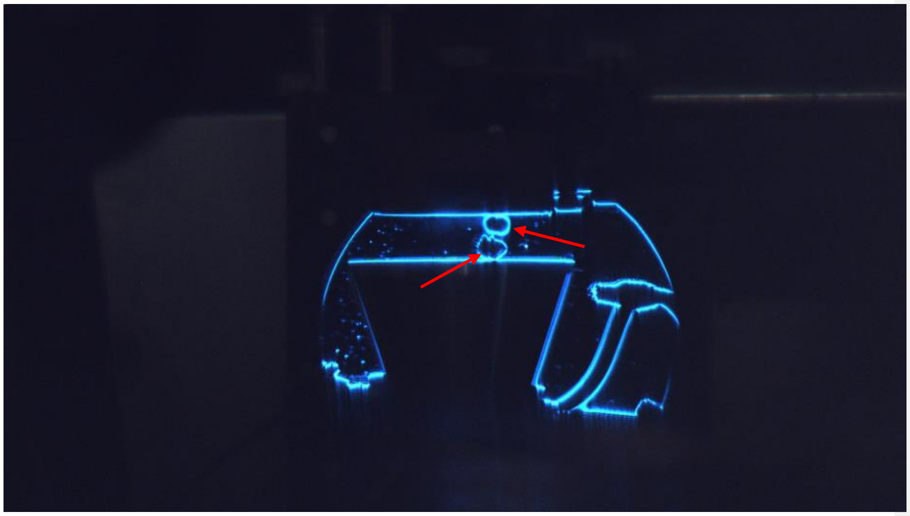


Figure 28: The Styrofoam particles levitating stably in the high-pressure zones at a separation distance of 14.11 mm. There is one particle for each layer of standing waves. The particles are denoted by the arrows.

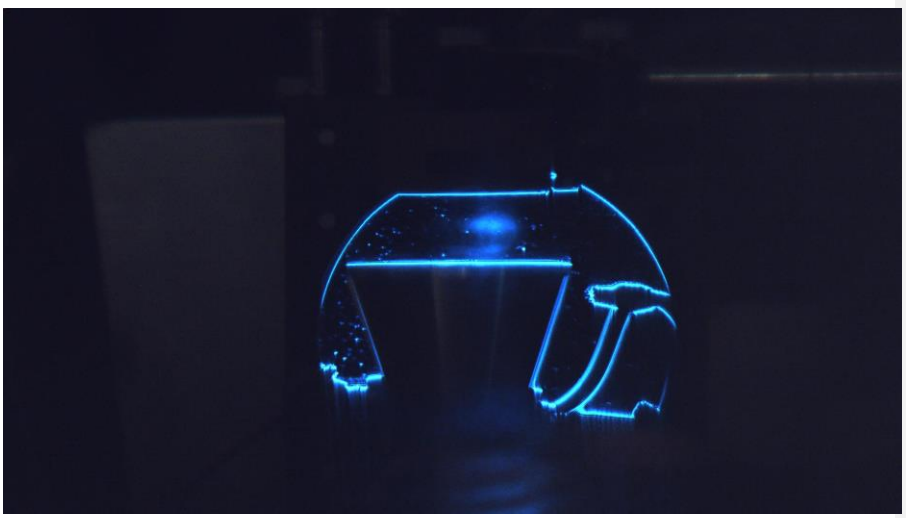


Figure 29: The acoustic standing waves created by the flat reflector at 21.09 mm. The blue is not as bright as the waves at the 14.11 mm separation distance, indicating that the waves are weaker as the separation distance increases. The waves are stacked on top of each other, creating three layers of waves.

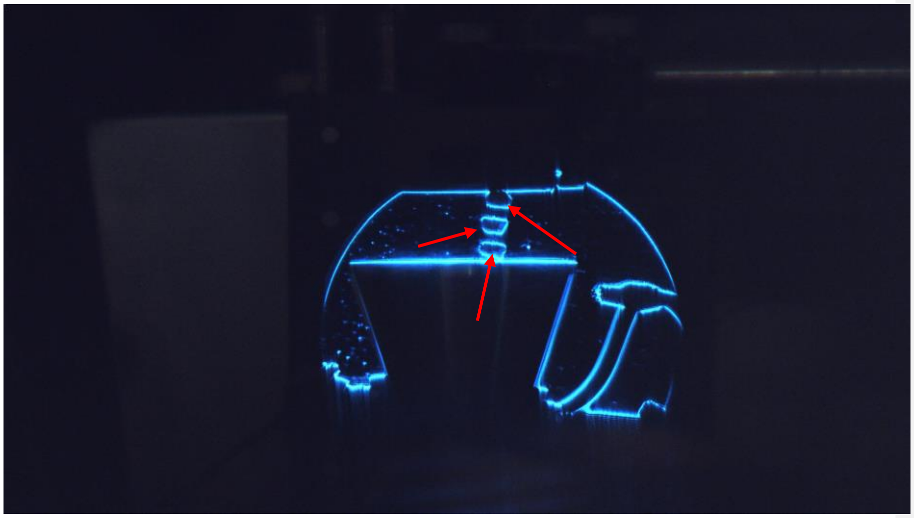


Figure 30: The Styrofoam particles levitating stably in the high-pressure zones at a separation distance of 21.09 mm. There is one particle for each layer of standing waves. The particles are denoted by the arrows.

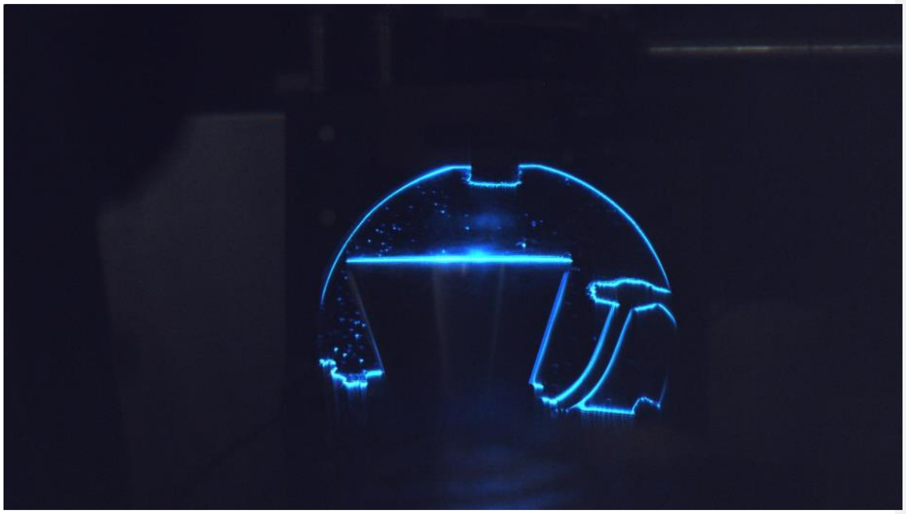


Figure 31: The acoustic standing waves created by the flat reflector at 28.09 mm. The blue is not as bright as the waves at the 21.09 mm separation distance, indicating that the waves are weaker as the separation distance increases. The waves are stacked on top of each other, creating four layers of waves.

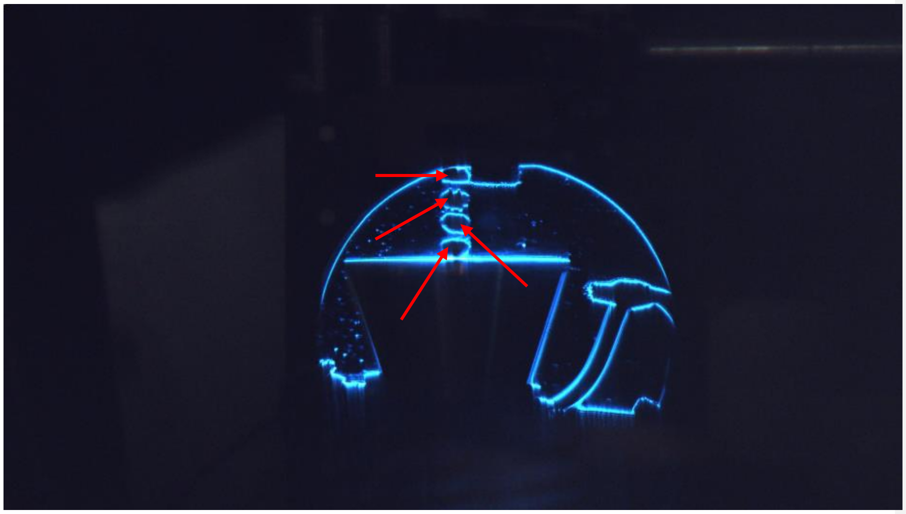


Figure 32: The Styrofoam particles levitating unstably in the high-pressure zones at a separation distance of 28.09 mm. There is one particle for each layer of standing waves. The particles are denoted by the arrows.

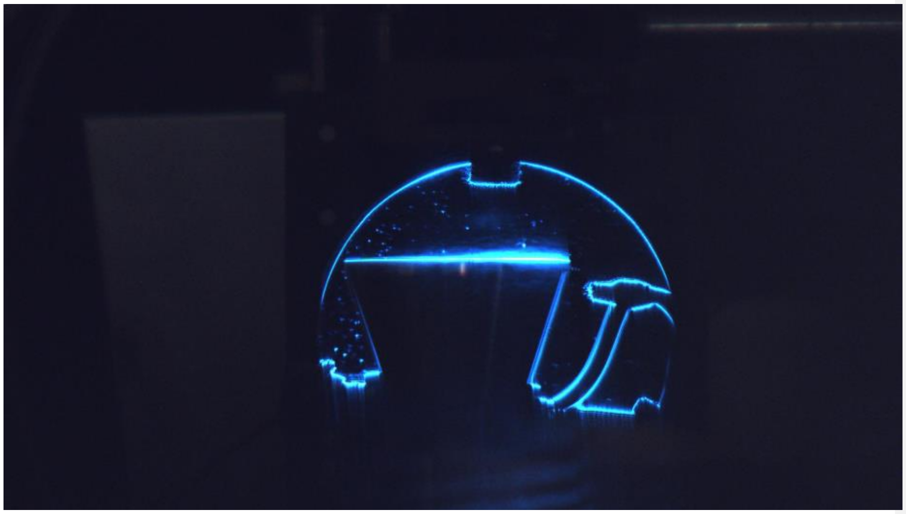


Figure 33: The acoustic standing waves created by the flat reflector at 35.00 mm. The blue is not as bright as the waves at the 28.09 mm separation distance and are barely visible, indicating that the waves are weaker as the separation distance increases. The waves are stacked on top of each other, creating five layers of waves.

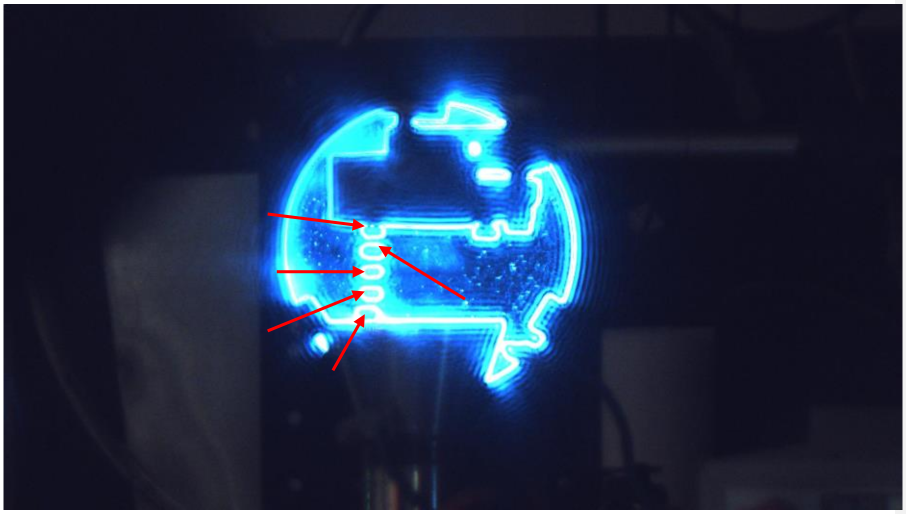


Figure 34: The Styrofoam particles levitating unstably in the high-pressure zones at a separation distance of 34.81 mm. There is one particle for each layer of standing waves. The particles are denoted by the arrows.

G. Performance of the Peltier Cooling Disk

For maximum efficiency when cooling, it is necessary for the thermoelectric Peltier cooling disk to follow the quadratic equation outlined in Van Baak's article "Temperature servomechanisms using thermoelectric modules"[1]. I observed temperatures for the levitator and the copper container that acts as the heat sink for the Peltier cooling plate in three scenarios: where the levitator was not running and the water was not being pumped through the system, where the levitator was running but water was not being pumped through the system, and where the levitator was running and the water was being pumped through the system. The results of these scenarios are outlined in the following tables.

CURRENT SUPPLIED TO PELTIER PLATE (A)	TEMPERATURE OF LEVITATOR (°C)	TEMPERATURE OF HEAT SINK (°C)
0	19.6	19.2
1	16.5	19.9
2	14.6	21.6
3	13.9	23.8
4	13.8	25.5
5	14.2	27.4

Table 1: A situation where the levitator is off, and no water is being pumped through the cooling system.

CURRENT SUPPLIED TO PELTIER PLATE (A)	TEMPERATURE OF LEVITATOR (°C)	TEMPERATURE OF HEAT SINK (°C)
0	19.4	22.1
1	18.8	22.9
2	17.8	23.8
3	16.9	25.3
4	16.6	26.3
5	16.9	28.6

Table 2: A situation where the levitator is on, but no water is being pumped through the cooling system.

CURRENT SUPPLIED TO PELTIER PLATE (A)	TEMPERATURE OF LEVITATOR (°C)	TEMPERATURE OF HEAT SINK (°C)
0	21.3	22.7
1	19.9	23.1
2	18.2	23.5
3	16.5	23.6
4	15.2	24.2
5	14.5	25.0
6	14.4	25.7
7	14.7	26.7
8	15.7	27.6
9	17.7	29.2

Table 3: A situation where the levitator is on, and water is being pumped through the cooling system.

Analysis

A. Performance of the Peltier Cooling Disk

As I mentioned in the previous section, the cooling device I implemented proved to reduce the diffraction of air by heat waves significantly enough to allow the refraction of the sound waves to show most prominently on the images captured by the FlyCap camera rather than the heat waves. This was in large part due to the thermoelectric Peltier cooling disk that I used. While the other cooling methods I originally implemented somewhat reduced the temperature of the levitator, none of them were as effective as my final method, which utilized Peltier cooling disk and water. To analyze the performance of the Peltier disk in my experiment, I fit my experimental data to a model outlined in the paper "Temperature servomechanisms using thermoelectric modules" by D. A. Van Baak[1]. In his experiment, Van Baak explored the properties of thermoelectric modules that exploit the Peltier effect and how they can be used to regulate temperature in different experiments and systems. Thermoelectric modules like the one I used for my experiment are in contact with two reservoirs while operating; the stage and the sink. For my experiment, the stage was the acoustic levitator while the sink was the copper box with water being cycled in and out of it. Without going into too much detail, Van Baak showed that when data about the temperature and current is taken with the thermoelectric modules, the temperature data fits a quadratic equation as current increases for both the stage and the sink. For the stage, while the temperature initially decreases, the temperature reaches a minimum before increasing as current continues to increase. For the sink, the temperature slowly increases as the current increases, with temperature increasing at a greater rate at higher currents. Van Baak provides a graph (Fig. 20) of this behavior in his paper.

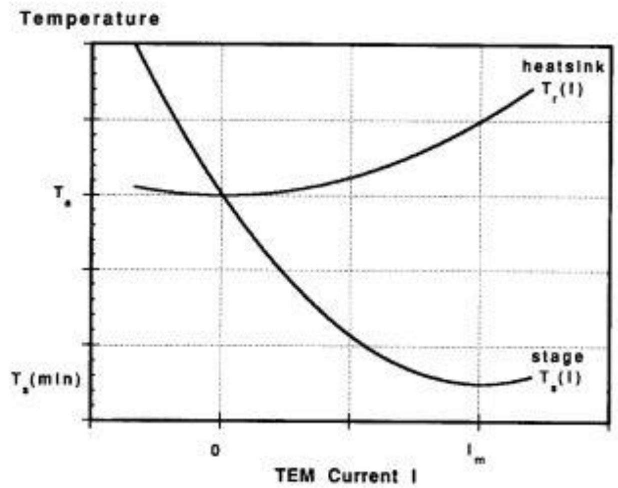
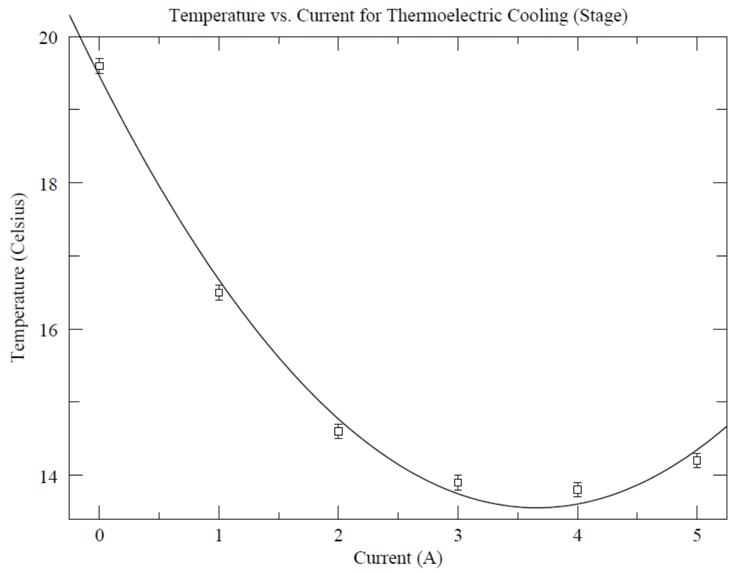
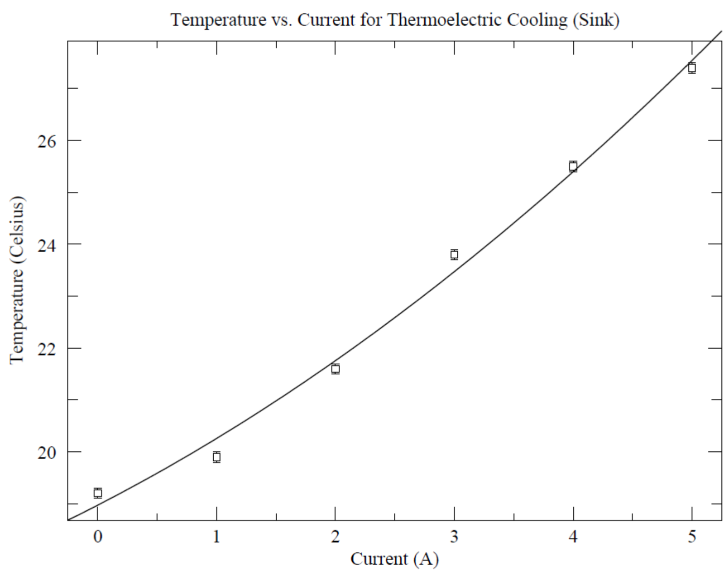


Figure 35: A graph of the current of the thermoelectric module versus the temperature of both the stage and the sink from Van Baak's paper "Temperature servomechanisms using thermoelectric modules".

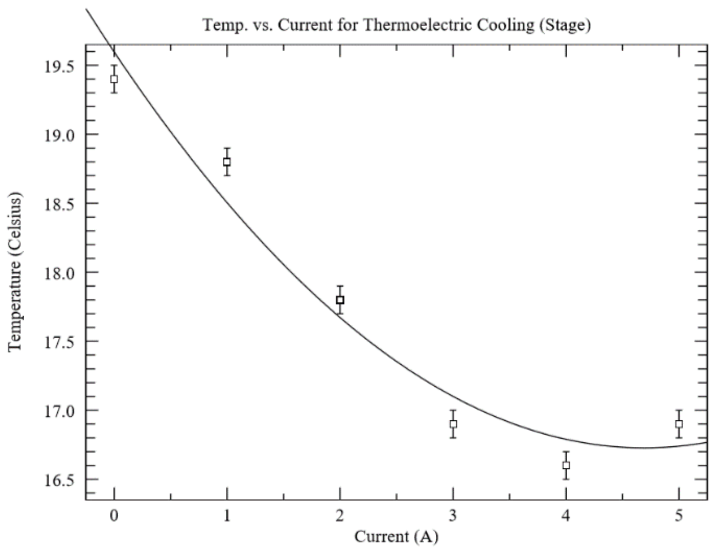
Outlined in the tables in the previous section, I fit my experimental data to a quadratic equation. When fitting my data, I chose to ignore error in the current, since it was negligible. The current to the thermoelectric Peltier disk was supplied by an DC power supply, and the values were displayed digitally by the device. The error in the readout on the device is negligible. The uncertainty in the temperature was 0.1 degrees Celsius. The temperature of the stage and the sink in my experiment was determined by a thermocouple. This device gave readings accurate to a tenth of a degree, and when a stable temperature was reached by the stage or the sink, the device would sometimes vary higher or lower by one tenth of a degree. I used the web-based WAPP+ fitting program to fit my experimental data for both the stage and sink to a quadratic equation. I recorded data for three different situations. The first is when the levitator was off and there was no water being cycled through the copper box. The second was when the levitator was running and there was no water running through the copper box. The third situation was when the levitator was running and there was water running through the copper box. For the first situation, I obtained a reduced chi-squared (χ^2) value of 11 for the sink and χ^2 = 5.4 for the stage. While these χ^2 values are relatively large, the graphs show that the data fits the quadratic equations fairly well.

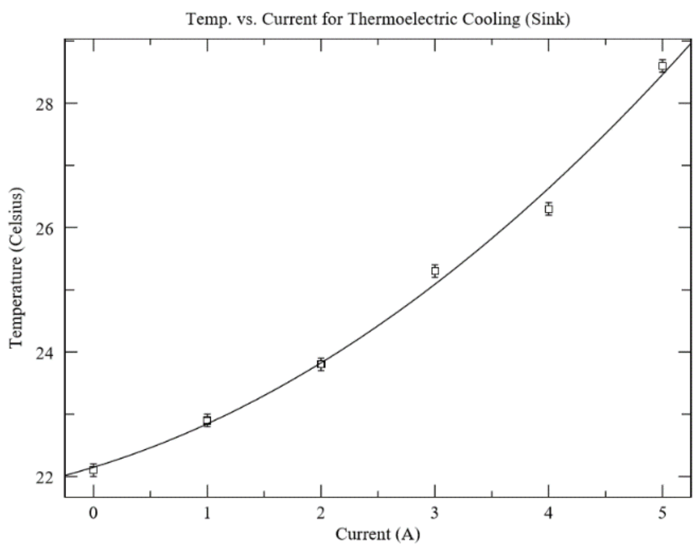




Figures 36 and 37: Graphs of a situation where the levitator is off and water is not being cycled through the copper box. The stage (levitator) is on the left and the sink (copper box) is on the right.

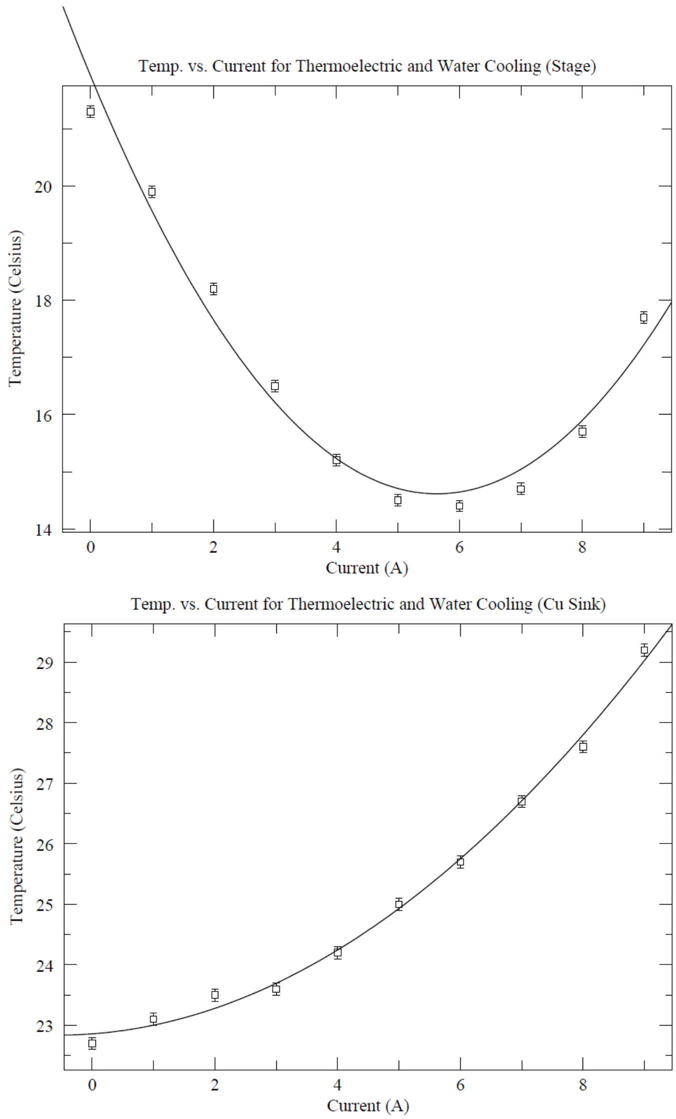
For the second situation, I determined χ^2 to be 6.0 for the sink and χ^2 to be 8.2 for the stage. While the data for the sink fits the quadratic equation, χ^2 for the stage is large. The graphs indicate, however, that the date fits the quadratic equation fairly well.





Figures 38 and 39: Graphs of a situation where the levitator is on and water is not being cycled in and out of the copper box. The stage (levitator) is on the left and the sink (copper box) is on the right.

For the third situation, I determined χ^2 to be 2.4 for the sink and χ^2 to be 20 for the stage. While the data for the sink fits the quadratic equation, χ^2 for the stage is large. The graphs indicate, however, that the date fits the quadratic equation fairly well.



Figures 40 and 41: Graphs of a situation where the levitator is on and water is being cycled in and out of the copper box. The stage (levitator) is on the left and the sink (copper box) is on the right.

B. Particle Levitation

During my experiment, I was not able to implement a way of measuring the properties of the levitation of particles besides observing them by sight. Using Styrofoam particles and the position of the sound waves given by the FlyCap camera, I was able to determine whether particles were levitating in high- or low-pressure zones. There are many papers that I compared my results to regarding the position of particles during levitation, including "Experimental and numerical characterization of the sound pressure in standing wave acoustic levitators"[2]. In that paper, the scientists found that the particles levitated in the high-pressure zones created by the minimum acoustic potential. In my experiment with the curved reflector, I found that particles could levitate in both high-and low-pressure zones. With the flat reflector, I found that particles could only levitate in high-pressure zones.

For the flat reflector, I observed acoustic standing waves at 6.89 mm, 14.11 mm, 21.09 mm, 28.09 mm, and 35.00 mm. With the acoustic levitator operating at a frequency of 25 kHz, that means that the wavelength of the standing waves is around 13.72 mm according to

$$\lambda = \frac{v}{f}, \tag{7}$$

where v is the speed of sound, which is 343 meters per second. According to the theory for acoustic levitation, the levitator should produce standing waves at distances one half of the wavelength above the levitator. The separation distances produced with the flat reflector are all fairly close to multiples of half the wavelength.

<u>Conclusion</u>

When analyzing the performance of the Peltier cooling disks, I achieved some values of χ^2 that were large. One reason that may have caused the large χ^2 values could have been the fact that the constants in Equations 5 and 6 can vary when exposed to a greater amount of heat. These constants include the ordinary heat conduction of the TEM, the Peltier heat flow of the TEM, the resistance of the TEM, and the thermal conductance of the radiator. As the temperature of the stage and the sink varied during my experiment, these constants may have fluctuated, resulting in a different value for the temperature of the TEM than was expected given the equations.

Another reason the χ^2 values were large may have been from oversimplifying Equations 5 and 6 when fitting the experimental data into WAPP+. The equations have many constants and variables in them. Fitting these two equations to a simple quadratic equation with one variable and three constants may not be a good enough approximation for the data. Fitting two complex equations to a simple model may have caused the large χ^2 values.

After overcoming the problem of trying to cool the transducer enough to have the acoustic standing waves be clearly visible to the FlyCap camera, it is now possible to conduct more experimentation with the acoustic levitator. With the heat waves at a fairly stable and insignificant level, now more experiments can be undertaken regarding the types of particles that can be levitated and the types of reflectors used during levitation. It would be interesting to see how different shaped reflectors produce different shaped pressure zones. It would also be interesting to see if the material of the reflector affects the amount of force produced by the standing waves.

I determined that for the concave reflector, the particles could levitate in both the high- and low- pressure zones, and for the separation distance at 19.46 millimeters, I could get two particles to levitate. Comparing these results to the findings in "Analysis of the particle stability in a new designed ultrasonic levitation device"[3], the authors found that the particles they experimented on only levitated in areas with minimal acoustic potential. According to Equation 1, areas with low acoustic potential have a high acoustic radiation force. This means that areas of high pressure (or the bright spots captured by the FlyCap camera) should be the only places where particles levitate with a concave reflector. For future experimentation, it would be interesting to capture images of the standing acoustic waves from two angles rather than just one. This would help determine if the particles really are levitating in both high- and low- pressure zones, or if they are only levitating in high-pressure zones that are obscured by the high-pressure zone closest to the camera.

For the flat reflector, I determined that particles only levitate in high-pressure zones. With the flat reflector, I was able to get up to five particles to levitate in each multiple of half the wavelength depending on the separation distance. Comparing these results to "An ultrasonic levitator"[4], the scientists who authored that paper found that the particles levitated below the node of the standing waves, or the antinode. This means that they found that particles also levitate in only the high-pressure zones, which in turn means my results are similar to theirs.

For future experimentation, one thing that would be interesting to investigate is trying to levitate different types of particles and which pressure zones they levitate in. I experimented a little with levitating water droplets, but I did not obtain enough data to go into detail on it. Another thing that would be interesting to investigate could be trying to measure how strong the acoustic radiation force is. I experimented a little with a program called ImageJ, and that program allowed the user to measure the brightness of the pixels in the image and produce a graph of the brightness through a certain segment of the image. It would be interesting if future experimenters could use this program and relate the data from that program to the acoustic radiation potential and force via Equations 1 and 2.

Acknowledgements

I would like to thank my advisor, Professor Dean Langley, first and foremost. His help and guidance allowed my experiment to progress as far as it did. Working through problems and discussing ideas with him was greatly beneficial to me. I especially appreciate all the extra hours he put in to make sure I had all the parts, instruments, materials, and space that I needed.

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I would also like to thank my family. I would like to thank my parents for helping me pay for my tuition, as well as providing me with all the essentials needed for college, in addition to the constant love and support. I would like to thank my fiancé Kennedy Stace for always being there for me and supporting me no matter what.

Lastly, I would like to thank CSB/SJU for accepting me four years ago and giving me the opportunity to further my education at this tremendous institution.

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2. Stindt A.; Andrade M. A. B.; Albrecht M.; Adamowski J. C.; Panne U.; Riedel J. “Experimental and numerical characterization of the sound pressure in standing wave acoustic levitators” Review of Scientific Instruments 85, 2014.
3. Baer S.; Andrade M. A. B.; Esen C.; Adamowski J. C.; Schweiger G.; Ostendorf A. “Analysis of the particle stability in a new designed ultrasonic levitation device” Review of Scientific Instruments 82, 2011.
4. Boullosa R. R.; Pérez-López A.; Dorantes-Escamilla R. “An ultrasonic levitator” Journal of Applied Research and Technology, Vol. 11, December 2013.
5. Langley D. S.; Marston P. L. “Generalized tertiary rainbow of slightly oblate drops: observations with laser illumination” Applied Optics 37, pg. 1520-1526, 1998.

Appendix

The following data is of the power output of the acoustic levitator, the power transmitted through the copper and into the water, and the power carried away by the water.

		Voltage	25	V		
		Current	0.5	A		
Levitator	Power In P = V*I	Power	12.5	W		
Copper	Thermal conductivity	k	390	W/m/K		
	Thickness	d	0.0125	m		
	Area	A	0.0025	m^2		
	Temperature difference	ΔT	0.2	K		
	Heat transfer rate	P = k*A*ΔT/d	15.6	W		
Thermoelectric module						
	TEC1-12712 Peltier module	A	0.0025	m^2		
	Max cooling power	Pmax	109	W		
Water	Specific Heat	c	4186	J/kg/K		
	Volume	V	0.001	m^3		
	Density	ρ	1000	kg/m3		
	Mass	m	1	kg		
Pump	Volume Flow Rate	V/t	1.2	L/min	20	cm^3/s
	Mass Flow Rate	m/t	0.020	kg/s	20	g/s
Power Out	P = Q/t = (m/t)*c*ΔT		17	W		