Determination of Capacitance's Effect on a Coil Gun's Muzzle Velocity

Jacky Li

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Physics 12

Mr. N. Westergaard

Abstract

A coil gun is a projectile device that utilizes the principles of electromagnetism and electronic circuits. In this experiment, a single-staged coil gun using an LC circuit was first constructed and a permanent magnet slug was used as the projectile. The effect of muzzle speed by capacitors with different capacitances while supplying the same voltage of 25V and a current of 0.01A was tested. The experimental muzzle velocity was measured with an IR sensor and calculated with kinematics equations, while the law of conservation of energy was used to calculate theoretical velocity. This experiment aimed to determine how different capacitances affect the muzzle velocity of a coil gun. Hobbyists can use this result to improve and optimize a coil gun's muzzle velocity by adjusting capacitance. It was found that the muzzle velocity squared is directly proportional to the capacitance. This also matched up with the theoretical estimations from the law of conservation of energy.

Introduction

A Coil gun, also referred to as a Gauss Rifle, is a type of mass driver using coils as electromagnets to accelerate conducting or ferromagnetic/permanent magnet projectiles. The coil gun does not involve any chemicals when launching. This makes it to be harmless to the environment. Many countries and organizations have been testing and improving this device as a military weapon or satellite launcher for outer space. The principle of a Gauss rifle is to launch the projectile by the sudden change of magnetic force inside a solenoid. When current is applied to a solenoid, A change of magnetic flux occurs inside the solenoid. This change in flux gives a repulsion to the projectile. The right-hand rule can determine the direction of the magnetic field, which will also be the launching direction of the projectile. The magnetic field strength inside a uniform solenoid is given by the formula $B = \frac{\mu n I}{L}$, where μ is the permeability of free space, n is the number of turns of the solenoid, I is the current of the solenoid, and L is the length of the solenoid.

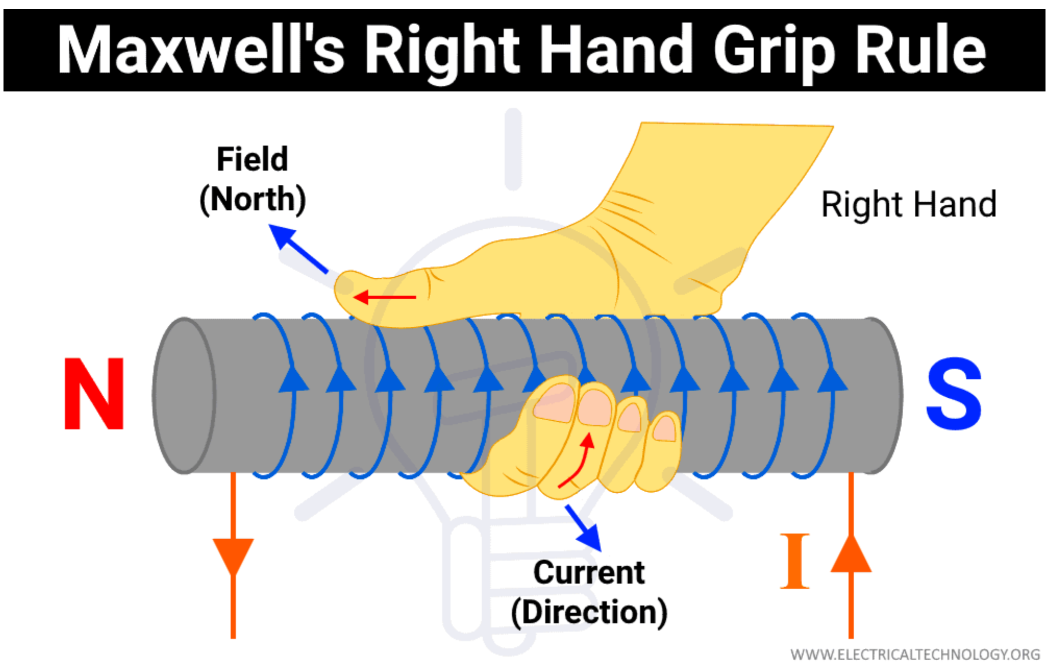


Figure 1. Right Hand Grip Rule for Solenoid

The projectile is launched using a resonant circuit (LC circuit) in this configuration. The inductors (L) and capacitors (C) are the two major components of this kind of circuit. In this setup, the inductor functions just like a solenoid. On the other hand, the capacitor is used for storing electrical energy. An electrolytic capacitor stores electrical energy within the two metal plates separated by a dielectric. The potential energy stored in a capacitor is given by the formula $\mathrm{E_p} = \frac{1}{2}\mathrm{CV}^2$, where C is the capacitance, and V is the voltage of the capacitor. This potential energy can be rapidly discharged and released. A sudden release of potential energy creates a sudden increase in magnetic flux inside the solenoid. The magnetic flux will drop to zero shortly after all the energy inside the capacitor is released. As the magnet slug has its own magnetic field, it interacts with the sudden increase in magnetic flux. The magnetic field generated by the solenoid and magnet slug creates a repulsive/attractive force. This propels the slug out of the barrel. If other energy storage devices such as batteries are used, a uniform magnetic force will be generated inside the solenoid. It will cause the projectile to be held inside the solenoid by the magnetic force instead of flying out. This explains that the important role of a capacitor in a coil gun is to release all its potential energy in a short instant.

Capacitance is the measurement of a system's capability to store electric charge. A capacitor's capacitance is represented as C and measured in farads (F), or $kg^{-1}m^{-2}s^4A^2$ in terms of SI base unit. When capacitors are connected in parallel, the total capacitance will be given by the formula:

$$\sum C = C_1 + C_2 + C_3 + \ldots + C_n$$

To determine the effect of capacitance on coil guns, capacitors are connected in parallel. When the only independent variable is the combinations of different capacitors in parallel, the effect of various capacitances on the muzzle velocity of the coil gun can then be determined. An

IR sensor is included to determine the velocity of the slug in this setup. It starts measuring the time when it receives the reflected infrared light. The IR sensor's infrared light is reflected by the magnet slug when it is fired. It can measure the time the slug uses to go from the front to the end. The muzzle velocity can be computed by the kinematics equation: $\vec{v} = \frac{\vec{d}}{\Delta t}$, where $\vec{d}$ is the length of the magnet slug, and Δt is the final time minus the initial time recorded by the IR sensor.

Materials

- PVC tube
- Copper wire
- Multimeter
- Capacitors with the capacitances wished to determine with
- Breadboard
- Soldering gun
- IR sensor
- DC power supply
- Permanent magnet slug
- Computer
- Arduino motherboard
- Tapes

Procedures

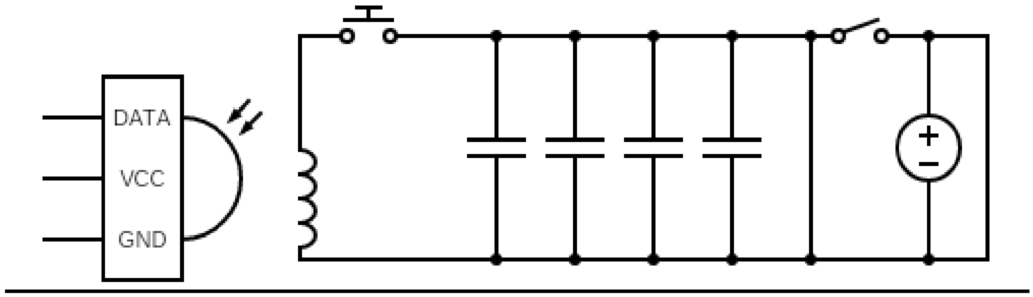


Figure 2. Circuit schematic diagram for the coil gun design

The switches in this schematic diagram represent the plugging and unplugging of electrical wires. This acts the same as mechanical switches. The term switches will be used in this paper.

1. Write the code for the IR sensor and set it up with an Arduino motherboard. For detailed information, see Appendix B.
2. Wrap around the PVC tube with the Copper Wire to make an inductor.
3. Line up and tape the IR sensor parallel to the coil. The IR emitter should be just right in front of the barrel.

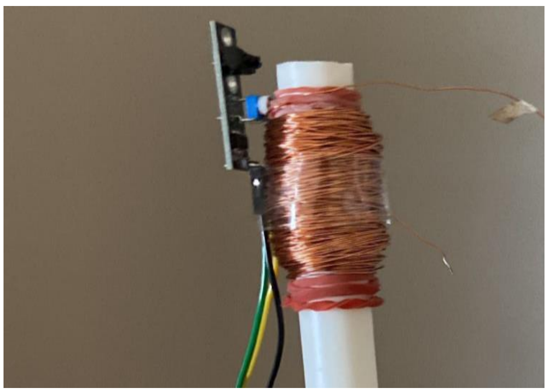


Figure 3. The IR sensor placement

4. Connect a capacitor in parallel with the inductor in the breadboard.
5. Use the DC power supply to charge up the capacitors to the maximum voltage they can stand. Open the switch between the capacitor and inductor.

6. Measure the voltage of the capacitance with the voltmeter.
7. Connect one terminal of the capacitor to the inductor. The switch between DC power and the capacitor must be opened.
8. Put the magnet slug inside the barrel. The magnet slug should just line up with the muzzle.

Figure 4. The placement of the magnet slug

9. Press the red button on the Arduino motherboard to reset the IR sensor.
10. Close the switch between the capacitors and the inductor to launch the slug.
11. Perform three trials per value of capacitance to reduce the uncertainty.
12. Repeat steps 4 to 11. More capacitors should be connected in parallel to increase the capacitance. A soldering gun might be used as the breadboard is not big enough to fit in too many capacitors

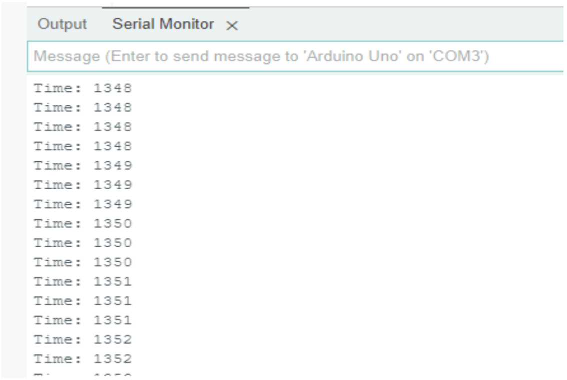
Results and Analysis

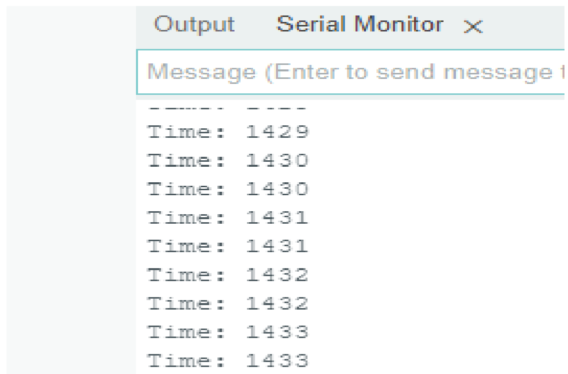
Mass of the magnet slug: 0.011 ± 0.005kg

Length of the magnet slug: 0.02 ± 0.005m

Voltage measured using voltmeter: 24.0 ± 0.5V

When the IR sensor detects the slug, it records the values from the initial time to the final time. The first trial of the capacitance 220 μF is demonstrated below as an example.





Figures 5 and 6. The initial and final time recorded by the IR sensor in ms

In Figure 5, the first value of 1348ms is the initial time. Where in Figure 6, the last value of 1433ms is the final time. The changes in time can be found as. $\Delta t = t_f - t_i = 1433 - 1348 = 85$ms. For raw data, see Appendix A. The table below summarizes all the results.

Capacitance(μF)	Time(ms)		
	Trial 1	Trial 2	Trial 3
220	85	88	100
440	44	45	46
660	26	28	31
1000	19	21	24
1320	16	17	16
1660	14	13	17
2200	19	16	15
4400	10	12	12
6600	9	10	10
8800	9	10	10

Table 1. Time recorded for each trial

After obtaining the time for each trial, the velocity in each trial is calculated by $\vec{v} = \frac{\vec{d}}{\Delta t}$.

Where d, the length of the slug is 0.02 m. The table below summarizes all the results.

Capacitance(μF)	Muzzle Velocity(m/s)			
	Trial 1	Trial 2	Trial 3	Average
220	0.24	0.23	0.20	0.22
440	0.44	0.44	0.43	0.44
660	0.71	0.71	0.65	0.69
1000	0.94	0.95	0.83	0.91
1320	1.22	1.18	1.25	1.22
1660	1.36	1.54	1.18	1.34
2200	1.2	1.25	1.3	1.26
4400	1.76	1.67	1.67	1.70
6600	2.07	2.00	2.00	2.02
8800	2.07	2.00	2.00	2.02

Table 2. Velocity for each trial and average velocity

From the table of values above, the relationship of capacitance versus muzzle velocity can be constructed. By using desmos, an optimized best-fit line can be denoted as shown on the following page.

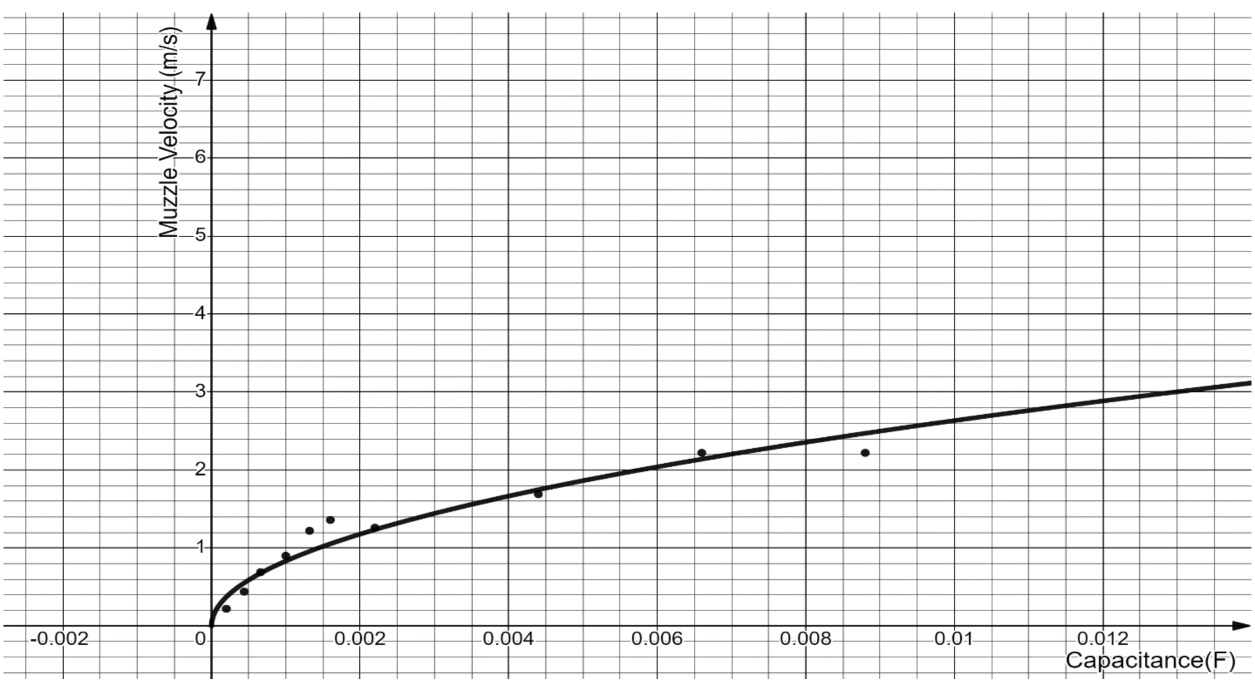


Figure 7. Best Fit Line for Muzzle Velocity vs Capacitance

It is computed by desmos that the graph behaves as a square root function, $v = \sqrt{bC}$. Where b is a constant value of 694, v is the muzzle velocity(y-axis) and C is the capacitance value(x-axis). To find the theoretical result of this experiment. One can use the law of conservation of energy Assuming there is no energy loss, all the potential energy stored in the capacitor will be released and converted to kinetic energy for the exit of the projectile. Knowing the energy stored in the capacitor is given by $E_p = \frac{1}{2}CV^2$. The theoretical muzzle speed can then be roughly estimated as:

$$E_p = E_k$$

$$\frac{1}{2}CV^2 = \frac{1}{2}mv^2$$

$$v = \sqrt{\frac{CV^2}{m}}$$

The theoretical velocity can then be found with the derived equation $v = \sqrt{\frac{CV^2}{m}}$ .When the mass of the slug is 0.011kg and the voltage supplied is 25V, the theoretical velocity function for this experiment is $v = \sqrt{\frac{(25)^2C}{0.011}} = \sqrt{56820C}$. For instance, when capacitance is 660 μF, the theoretical velocity is: $v = \sqrt{56820C} = \sqrt{(56820)(660 \times 10^{-6})} = 6.12\mathrm{m/s}$. By finding the theoretical velocity with the equation, the efficiency of the setup in each trail can also be found as: $Efficency = \frac{Experimental\ Velocity}{Theortical\ Velocity} \times 100\%$. A sample calculation with capacitance of 660 μF is shown: $Efficency = \frac{0.69}{6.12} \times 100\% = 11.24\%$. By repeating the same calculation for all trials, this setup's efficiency was averaged out as 11.7%. For detailed efficiency among each trail, refer to Appendix C.

Discussion

According to the derived equation $v = \sqrt{\frac{CV^2}{m}}$, the velocity squared is directly proportional to the capacitance, or mathematically speaking, $v^2 \propto C$. This matches up with the experimental variation. It shows that the muzzle velocity of a coil gun can be optimized by increasing capacitance.

However, the efficiency of this design can be improved. The average efficiency among all trials is only 11.7%. Multiple reasons can explain the low efficiency. The major reason is the design of the circuit. In this experiment, only a basic LC circuit with is used. This makes the experiment performable for people without a strong science background while demonstrating the relationship between muzzle velocity and capacitance. Yet, efficiency will be lower due to the simplified design. Multiple factors not accounted for in this circuit design can drastically affect the efficiency and accuracy of the muzzle velocity. For instance, the setup does not wrap the inductor as a uniform solenoid. This means that the magnetic field strength is not uniform along the inside of the inductor. However, the slug is placed in the front of the barrel for consistency to lower the uncertainty. Likely, the slug is not in the position with the strongest magnetic field. It then lowers the muzzle speed and the efficiency of the experiment. Another problem in the design is about the discharge time of the capacitor. The discharge time can be found precisely by using equipment like an oscilloscope. It is important to determine this number especially in a multi-stage coil gun where it is necessary to control the timing in each coil to maximize efficiency.

When considering the source of errors, one of the errors is the percentage error in voltage. Even though all the capacitors are charged to 25V shown by the DC power supply. The actual voltage charged is 24.0 ± 0.5V measured by the voltmeter. Another notable source of error is the accuracy and limitation of the IR sensor. It was found that when the value of capacitance is beyond 6600μF. The IR sensor can only measure a minimum time of 9ms. The reason for this is that when the velocity is too high, the IR sensor cannot measure the slug's time traveled precisely. This also explains the same result when capacitances are 6600μF and 8800μF. To reduce the uncertainties given by these two sources, equipment with higher accuracy will be required. Some other errors include the work done by friction between the PVC tube and the magnet slug, the inefficient aerodynamic shape of the slug etc.

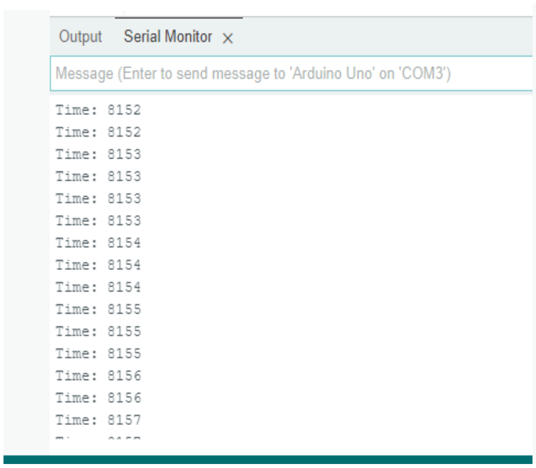
Lastly, it should be noted that some of the sources of error like the energy loss from resistance also lower the efficiency while increasing the uncertainty. The same thing is applicable to the factors that cause low efficiency.

Conclusion

In conclusion, the best-fit curve function was found to be $v = \sqrt{697C}$. The relationship between the muzzle velocity and capacitance of a coil was therefore found to be in square root relationship. This variation matches up the theoretical result, so the experiment supports the theory. The data is helpful for those hobbyists that would like to optimize a self-built coil gun by adjusting capacitance. It should also be noted that the effect of capacitance on muzzle velocity minimizes when the capacitances are too large because of the nature of square root relations. Although the relationship was found successful, many improvements can be made to improve this experiment. The uncertainty in this experiment is large and hard to quantify while the efficiency is low with an average of 11.7%. These aspects can be improved by a more thoughtful circuit design and more precise equipment etc.

Appendices

Appendix A: Raw Data of Time Collected from IR Sensor with Different Capacitances



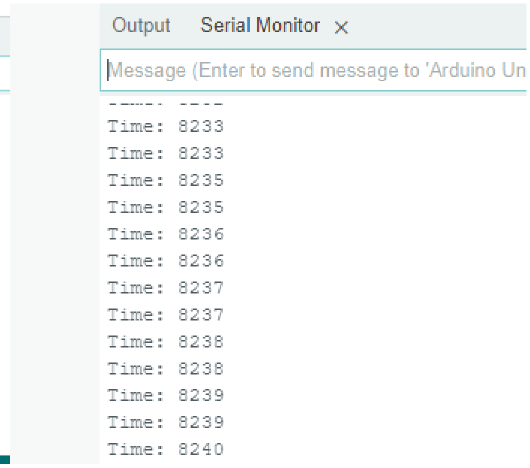


Figure A- 1 and 2. 220μF Trail 2

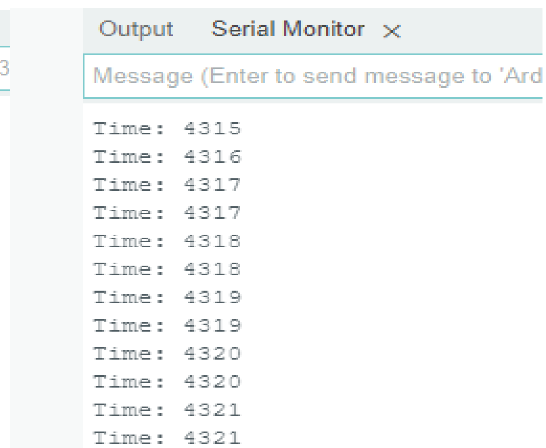


Figure A- 3 and 4. 220μF Trail 3

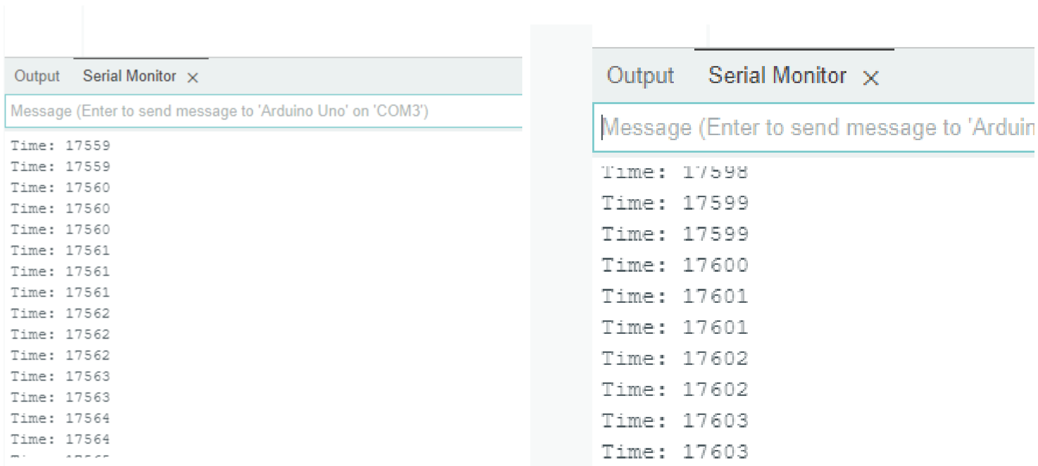


Figure A- 5 and 6. 440μF Trail 1

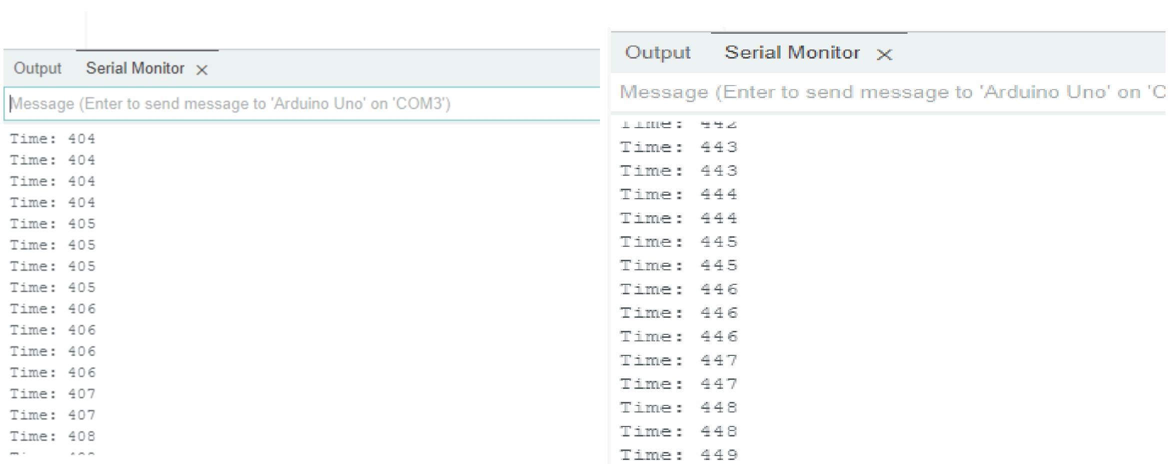


Figure A- 7 and 8. 440μF Trail 2

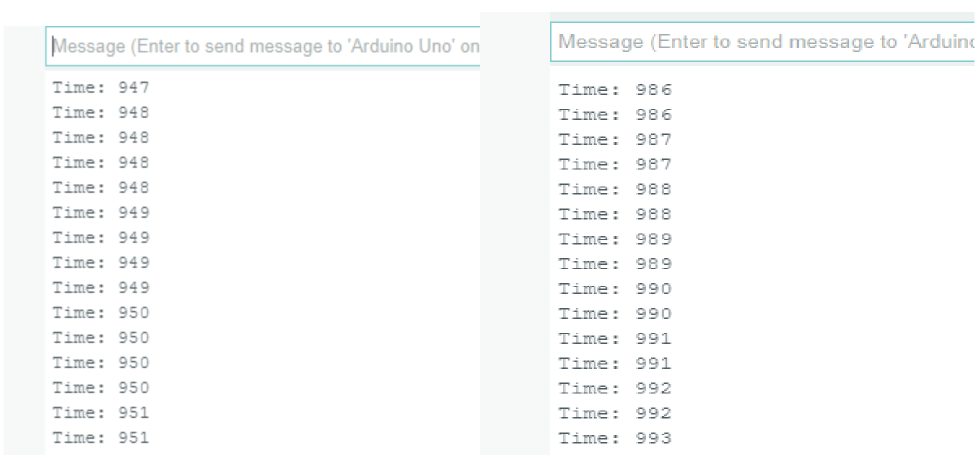


Figure A- 8 and 9. 440μF Trail 3

```
Time: 4599
Time: 4599
Time: 4600
Time: 4600
Time: 4600
Time: 4600
Time: 4601
Time: 4601
Time: 4601
Time: 4602
Time: 4602
Time: 4602
Time: 4603
Time: 4603
```

```
Time: 4618
Time: 4619
Time: 4619
Time: 4620
Time: 4621
Time: 4621
Time: 4622
Time: 4622
Time: 4623
Time: 4623
Time: 4624
Time: 4624
Time: 4625
```

Figure A- 10 and 11. 660μF Trail 1

```
Time: 12861
Time: 12862
Time: 12862
Time: 12862
Time: 12863
Time: 12863
Time: 12863
Time: 12864
Time: 12864
Time: 12864
Time: 12865
Time: 12865
Time: 12866
Time: 12866
Time: 12867
```

Output Serial Monitor ×

Message (Enter to send message to 'Arduino Uno' on 'CO

```
Time: 12881
Time: 12882
Time: 12882
Time: 12883
Time: 12883
Time: 12884
Time: 12884
Time: 12886
Time: 12887
Time: 12887
Time: 12888
Time: 12888
Time: 12889
```

Figure A- 11 and 12. 660μF Trail 2

```
Time: 1817
Time: 1817
Time: 1818
Time: 1818
Time: 1818
Time: 1819
Time: 1819
Time: 1819
Time: 1820
Time: 1820
Time: 1820
Time: 1820
Time: 1821
Time: 1821
Time: 1822
```

```
Time: 1841
Time: 1841
Time: 1842
Time: 1842
Time: 1843
Time: 1844
Time: 1844
Time: 1845
Time: 1845
Time: 1846
Time: 1846
Time: 1847
Time: 1847
Time: 1848
Time: 1848
```

Figure A- 12 and 13. 660μF Trail 3

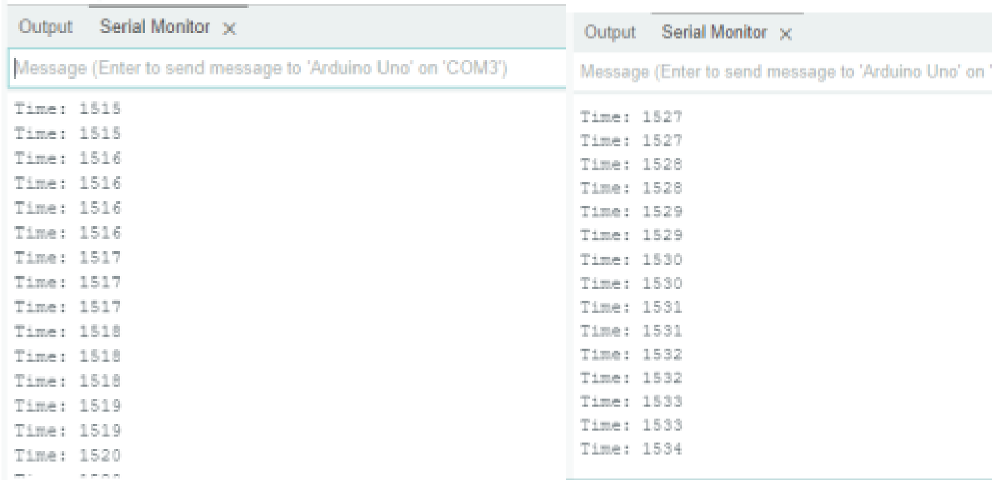


Figure A- 13 and 14. 1000μF Trail 1

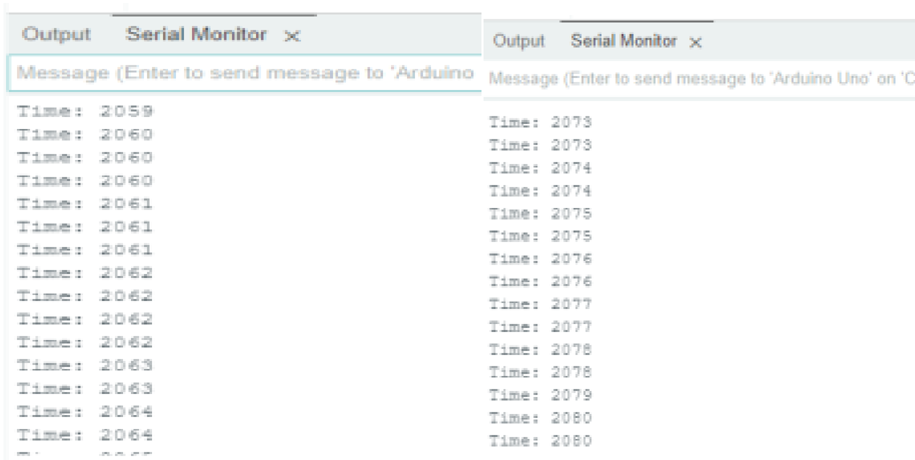


Figure A- 15 and 16. 1000μF Trail 2

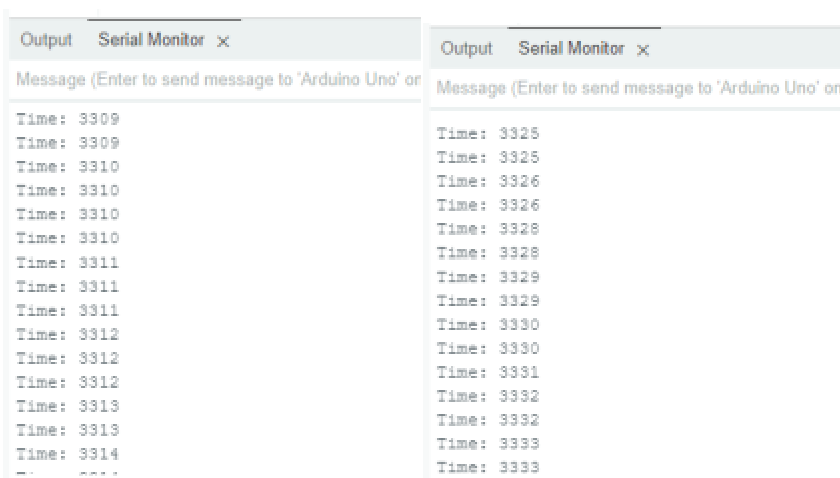


Figure A- 16 and 17. 1000μF Trail 3

```
Time: 11337
Time: 11337
Time: 11337
Time: 11338
Time: 11338
Time: 11338
Time: 11339
Time: 11339
Time: 11339
Time: 11340
Time: 11340
Time: 11341
Time: 11341
Time: 11342
Time: 11342
```

```
Time: 11344
Time: 11344
Time: 11345
Time: 11346
Time: 11346
Time: 11347
Time: 11347
Time: 11348
Time: 11348
Time: 11350
Time: 11351
Time: 11351
Time: 11352
Time: 11352
Time: 11353
```

Figure A- 18 and 19. 1320μF Trail 1

```
Message (Enter to send message to 'Arduino U
Time: 1297
Time: 1297
Time: 1297
Time: 1297
Time: 1298
Time: 1298
Time: 1298
Time: 1299
Time: 1299
Time: 1299
Time: 1299
Time: 1300
Time: 1300
Time: 1301
Time: 1301
```

```
Message (Enter to send message to 'Ard
Time: 1307
Time: 1307
Time: 1308
Time: 1308
Time: 1309
Time: 1309
Time: 1310
Time: 1310
Time: 1311
Time: 1311
Time: 1312
Time: 1312
Time: 1313
Time: 1313
Time: 1314
```

Figure A- 19 and 20. 1320μF Trail 2

```
Output   Serial Monitor ×
Message (Enter to send message to 'Arduino Uno' on 'C
Time: 8393
Time: 8393
Time: 8394
Time: 8394
Time: 8394
Time: 8395
Time: 8395
Time: 8395
Time: 8396
Time: 8396
Time: 8396
Time: 8396
Time: 8397
Time: 8397
Time: 8398
```

```
Message (Enter to send message to 'Arduino Uno'
Time: 8401
Time: 8401
Time: 8402
Time: 8402
Time: 8403
Time: 8403
Time: 8404
Time: 8404
Time: 8406
Time: 8406
Time: 8407
Time: 8407
Time: 8408
Time: 8408
Time: 8409
```

Figure A- 20 and 21. 1320μF Trail 3

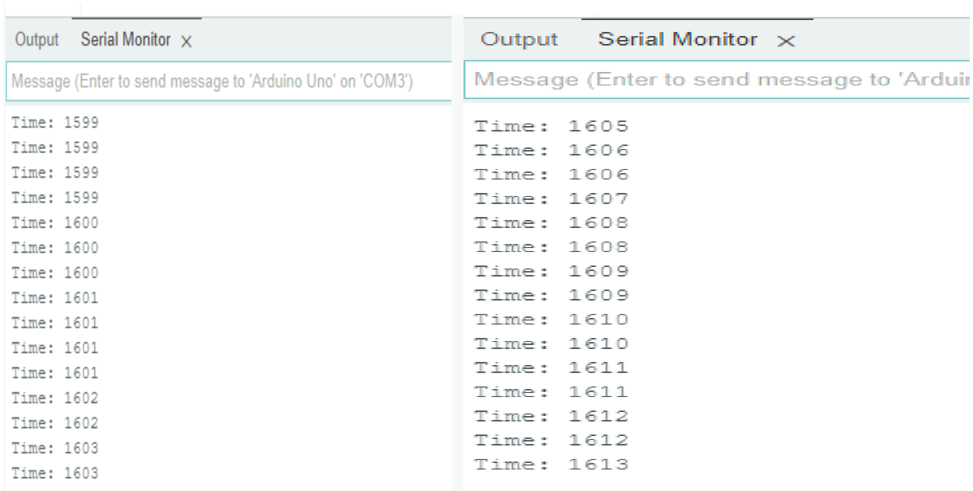


Figure A- 21 and 22. 1660µF Trail 1

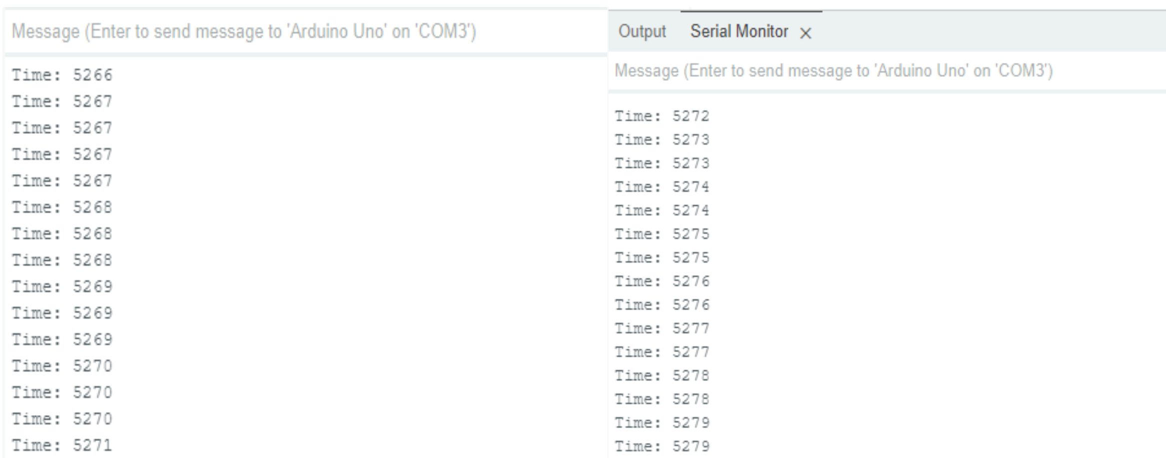


Figure A- 23 and 24. 1660µF Trail 2

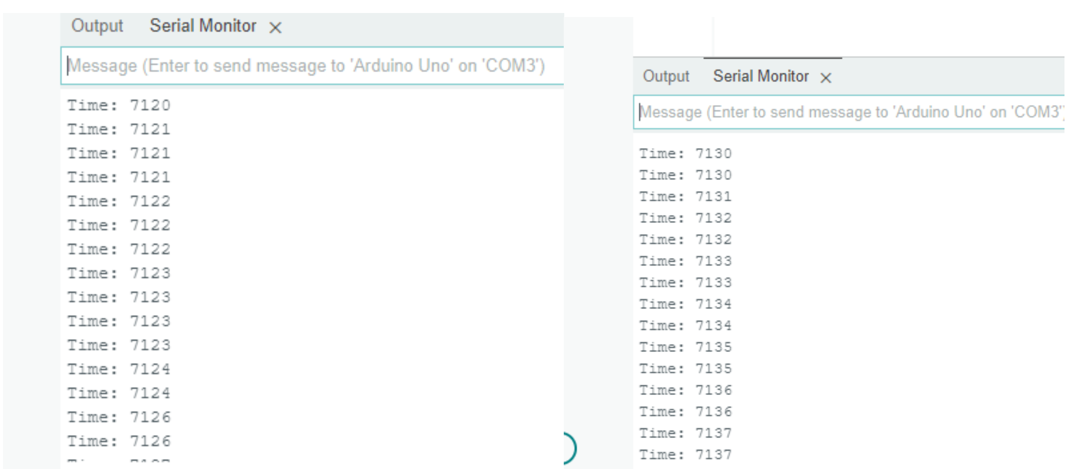


Figure A- 25 and 26. 1660µF Trail 3

```
Output    Serial Monitor ×
Message (Enter to send message to 'Arduino Uno' or
Time: 132
Time: 138
Time: 138
Time: 138
Time: 138
Time: 139
Time: 139
Time: 139
Time: 139
Time: 140
Time: 140
Time: 140
Time: 140
Time: 141
Time: 141
```

```
Output    Serial Monitor ×
Message (Enter to send message to 'Arduino Un
Time: 144
Time: 144
Time: 145
Time: 145
Time: 146
Time: 146
Time: 147
Time: 147
Time: 148
Time: 148
Time: 149
Time: 149
Time: 150
Time: 150
Time: 151
```

Figure A- 27 and 28. 2200µF Trail 1

```
Output    Serial Monitor ×
Message (Enter to send message to 'Arduino Uno
Time: 2075
Time: 2075
Time: 2075
Time: 2075
Time: 2076
Time: 2076
Time: 2076
Time: 2077
Time: 2077
Time: 2077
Time: 2078
Time: 2078
Time: 2078
Time: 2079
Time: 2079
```

```
Output    Serial Monitor ×
Message (Enter to send message to 'Arduino Ur
Time: 2083
Time: 2084
Time: 2084
Time: 2085
Time: 2085
Time: 2086
Time: 2086
Time: 2087
Time: 2087
Time: 2088
Time: 2088
Time: 2089
Time: 2089
Time: 2091
Time: 2091
```

Figure A- 29 and 30. 2200µF Trail 2

```
Output    Serial Monitor ×
Message (Enter to send message to 'Arduino Uno' c
Time: 2342
Time: 2342
Time: 2342
Time: 2342
Time: 2343
Time: 2343
Time: 2343
Time: 2344
Time: 2344
Time: 2344
Time: 2344
Time: 2345
Time: 2345
Time: 2347
Time: 2347
```

```
Output    Serial Monitor ×
Message (Enter to send message to 'Arduino Uno
Time: 2349
Time: 2350
Time: 2350
Time: 2351
Time: 2352
Time: 2352
Time: 2353
Time: 2353
Time: 2354
Time: 2354
Time: 2355
Time: 2355
Time: 2356
Time: 2356
Time: 2357
```

Figure A- 31 and 32. 2200µF Trail 3

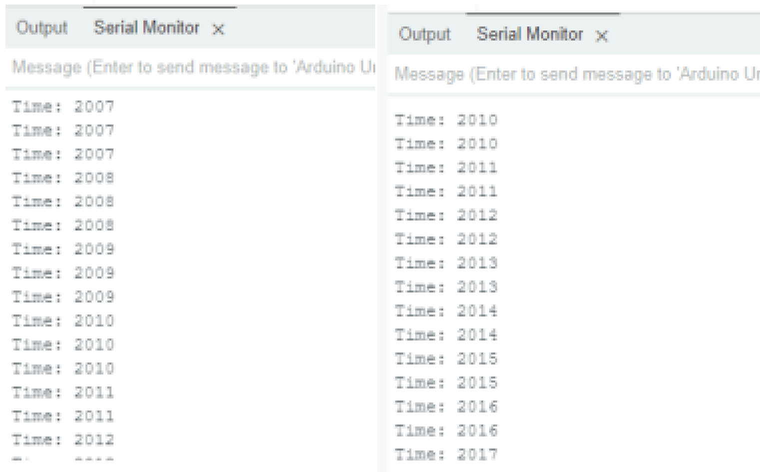


Figure A- 33 and 34. 4400µF Trail 1

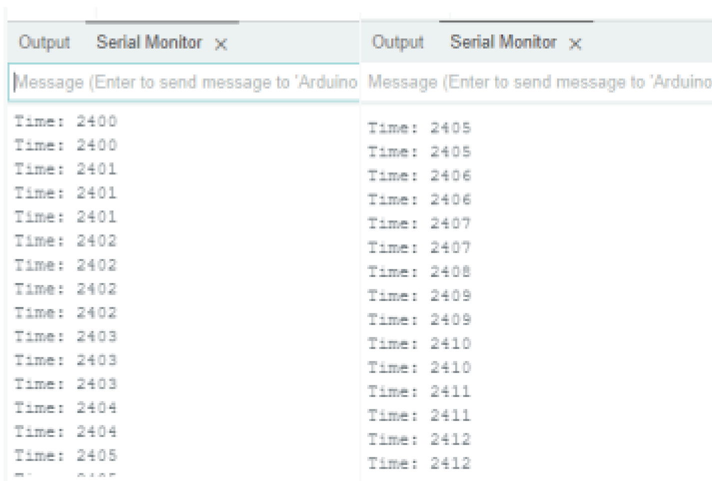


Figure A- 35 and 36. 4400µF Trail 2

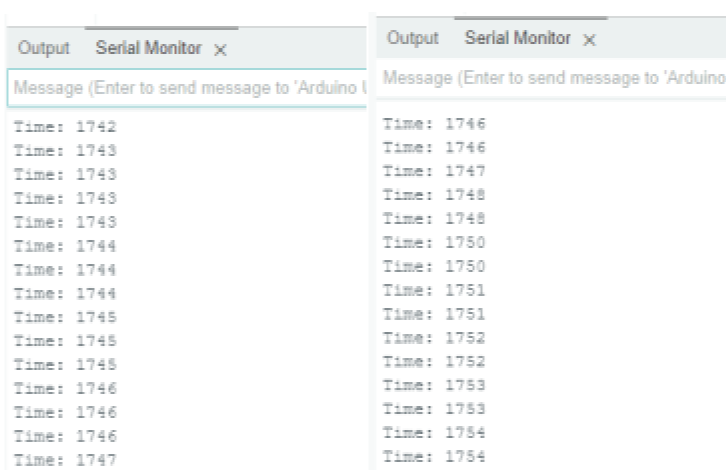


Figure A- 37 and 38. 4400µF Trail 3

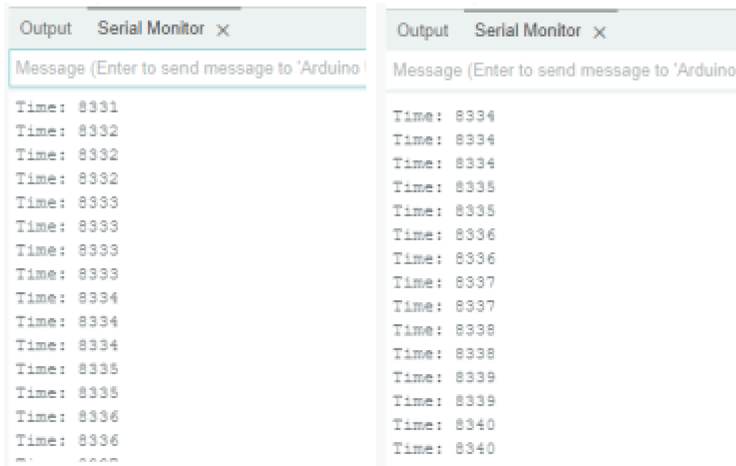


Figure A- 39 and 40. 6600μF Trail 1

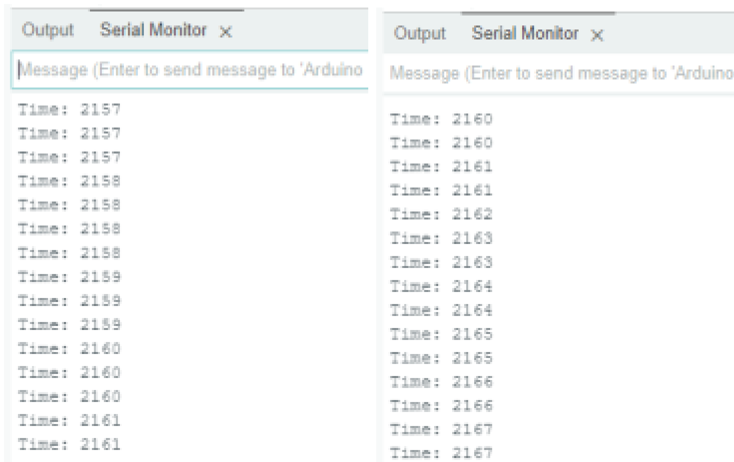


Figure A- 39 and 40. 6600μF Trail 2

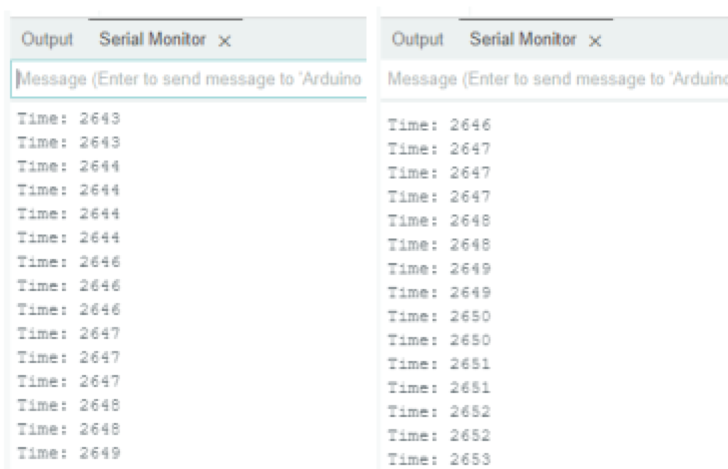
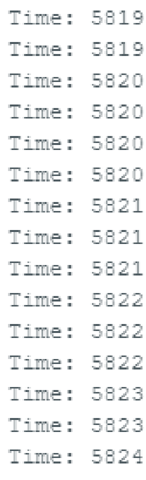


Figure A- 39 and 40. 6600μF Trail 3



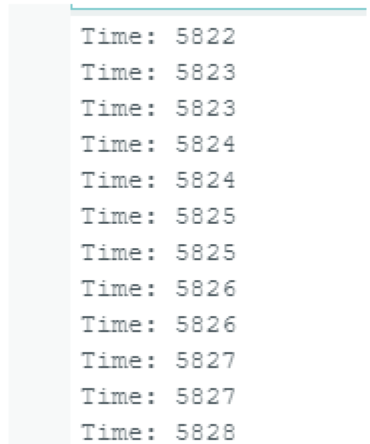


Figure A- 41 and 42. 8800μF Trail 1

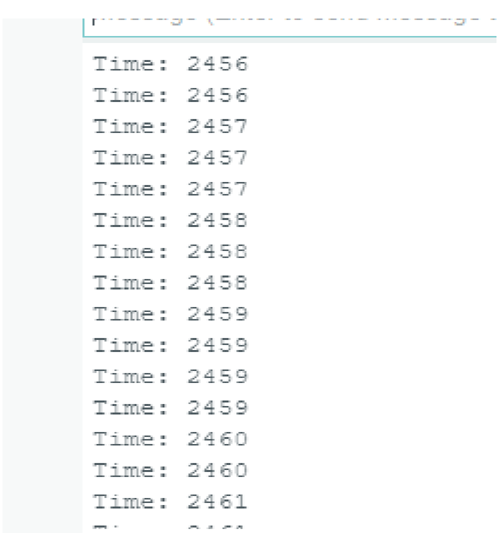
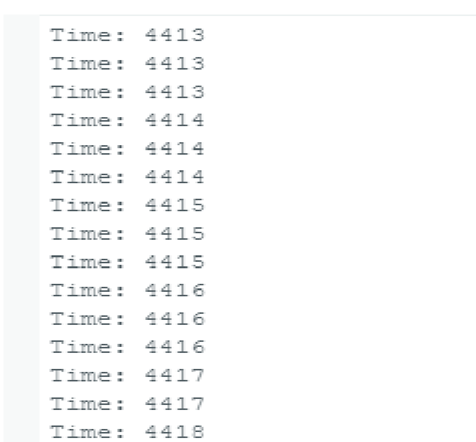


Figure A- 43 and 44. 8800μF Trail 2



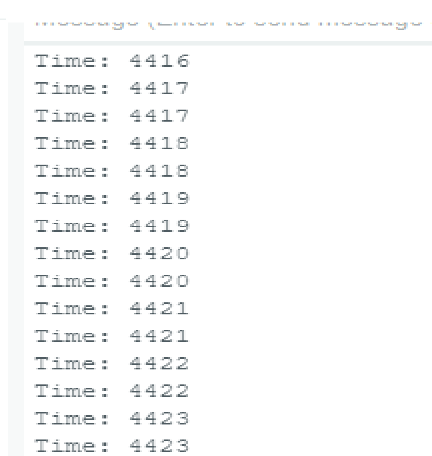


Figure A- 45 and 46. 8800μF Trail 3

Appendix B:

IRsesor.ino

```
int Sensor_pin = 2;
int value;
unsigned long myTime;

void setup ()
{
  pinMode (Sensor_pin  , INPUT);
  Serial.begin(230400);
}

void loop()
{
  value = digitalRead(Sensor_pin);
  if(value == LOW)
  {
    Serial.print("Time: ");
    myTime = millis();
    Serial.println(myTime);
  }
}
```

```
time = float(input("fdfd: "))

#print(time*0.001)

#dt = t1 - t2

velocity = 0.02/(time*0.001)

print(velocity*velocity)
```

Figure B-1 Code required for IR sensor **Figure B-2 Code for Muzzle Velocity calculations**

Appendix C: Efficiency for each trail

Capacitance(μF)	Average Velocity(m/s)	Theoretical Velocity(m/s)	Efficiency(%)
220	0.22	3.54	6.25
440	0.44	5.00	8.82
660	0.69	6.12	11.24
1000	0.91	7.54	12.04
1320	1.22	8.66	14.05
1660	1.34	9.71	14.00
2200	1.26	11.18	11.28
4400	1.70	15.81	10.75
6600	2.02	19.36	10.45
8800	2.02	22.36	9.05

Table C- 1.

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