NUS Summer Research Internship 2016

Takeaways, lessons learned and advice for future interns

Project Title: *Recreating Great Discoveries in Science and Engineering*

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1.0 Introduction

For two months in 2016, the authors of this paper worked closely with Dr. Anjam Khursheed in order to recreate a number of different inventions. Each of the recreated inventions played a key role in the development of the fields of science and engineering. A water pump, based on a design pioneered by Ctesibius, an ancient Greek scholar, was designed and manufactured. Moreover, a set of induction coils and a simple sterling engine were also designed and created. In order to ensure that each of the apparatuses could function effectively as an educational tool, the following design choices were emphasized:

- Manufacturability – Ensuring that the apparatuses were easily manufacturable was of capital importance to this project. A device that either requires great manufacturing skill, special machines or a large amount of manufacturing time is not effective as an educational tool because teachers will not be able to effectively make recreate them themselves.
- Reliability – Demonstrations need to function reliably. A demonstration that does not function properly is never effective and can often make the people observing the demonstration frustrated or confused.
- Demonstrability – The functionality of the device needs to be demonstrable. This allows students to not only see the device working, but also learn about how it works.

The overall purpose of the proceeding document is twofold. Firstly, each of the three prototyped designs will be described in detail. Specifically, the manufacturing process will be outlined and a standard operating procedure will be presented. Any key technical specifications will also be highlighted. Next, a series of improvements that could be made by future interns to our designs will be suggested. It is the author's hope that this document should make it considerably easier for future interns to continue working on this project in the future.

2.0 Water Pump

The water pump that was prototyped was based on an ancient design developed by Ctesibius, a Greek engineer. Ctesibius presented a design for a water pump that used two "flap" style valves. Figure 1 provides an illustration of the basic premise surrounding the valve system in a Ctesibius water pump. A variation of this valve system was used in the prototyped water pump.

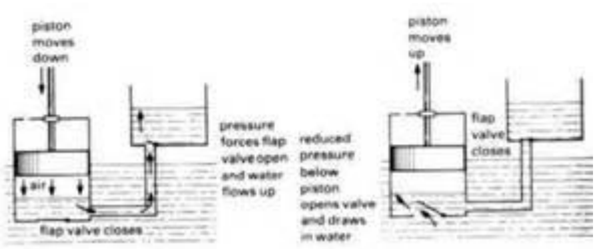

Figure 1: Basic premise of a Ctesibius water pump [2]

2.1 Overall Description

The pump was manufactured almost entirely out of acrylic. Acrylic was chosen as the primary material because it was readily available and waterproof. Additionally, the team had regular access to a laser cutter, making it easy to shape the material into the required dimensions. All parts of the pump were made out of acrylic with the exception of the piston, which was made of wood, the crankshaft axis, which was made of copper metal, and the valves, which were made of rubber.

The water pump is divided into five main components:

1. **Primary cylinder (holding cylinder):** The primary cylinder is responsible for taking in water with the help of the piston. It includes a valve to ensure that water does not escape even after the piston is removed.
2. **Secondary cylinder:** The water is pumped into the secondary cylinder, which can be thought of as a reservoir. Like the primary cylinder, the secondary cylinder also includes a valve that prevents water from escaping.
3. **Piston:** Water is pumped through the cylinders using the piston, which uses an o-ring to maintain a tight seal between the walls of the primary cylinder and the piston.
4. **Base:** The fourth component of the water pump is the base. The base holds the entire assembly together and was designed in order to be lightweight as well as stable. Note that the container that holds the water is an integral part of the base assembly. The base cannot be used without the container, which is, in our specific case, a small, metal pot.
5. **Crankshaft:** The fifth and final component of the pump is the crankshaft. The crankshaft mechanism increases the usability of the pump by allowing the user to use rotational force instead of vertical force, which is more awkward, to operate the pump.

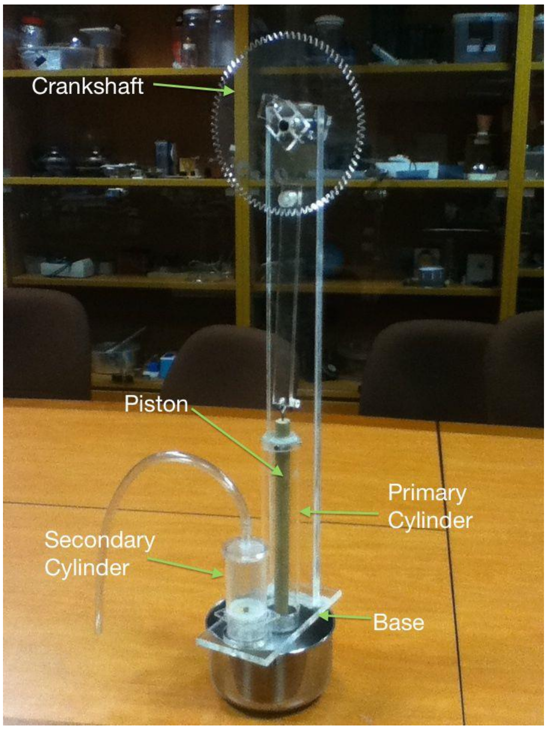

Figure 2: Prototyped water pump

2.2 Manufacturing process

This section of the report provides a detailed description of how we manufactured each of the different parts of the water pump. For the sake of brevity, only those parts that were either time consuming or troublesome to manufacture will be mentioned here.

2.2.1 Valves

The valves were made out of a thin, silicone rubber (rubber thickness = 2mm). Silicone rubber was chosen because it was readily available inside the lab. The procedure below outlines the steps completed during the manufacturing process:

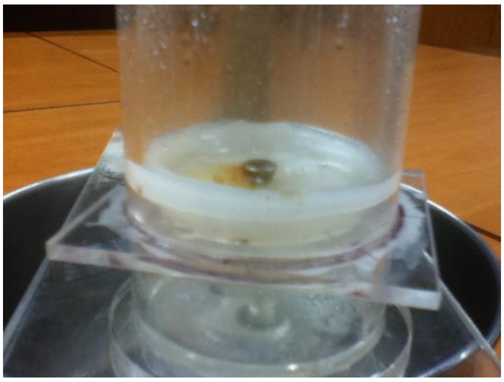

Figure 3: Secondary cylinder valve

- Cut a circle of rubber that is approximately 4mm in diameter **larger** than the inner diameter of the primary cylinder. The diameter of the rubber circle is absolutely crucial if the valve is to work properly. It must be larger than the inner diameter of the tube to prevent leakage.
- Using a pin, or some scissors, cut a small hole large enough for an M3 self-drilling screw to pass through smoothly.
- Select an appropriate base for the primary cylinder. The base should be the same size as the primary cylinder. Acrylic is the best material to use here.
- Using a drill press, drill a few holes into the base of the cylinder. One hole should be at the very centre of the piece, whereas the other 8 holes should be placed so that they form a circle just inside the inner wall of the primary cylinder. Figure 4 illustrates the hole arrangement. The outer holes are supposed to allow water to enter the cylinder whereas the centre hole allows the user to attach the rubber to the acrylic base. 3mm drill bits worked most effectively here.

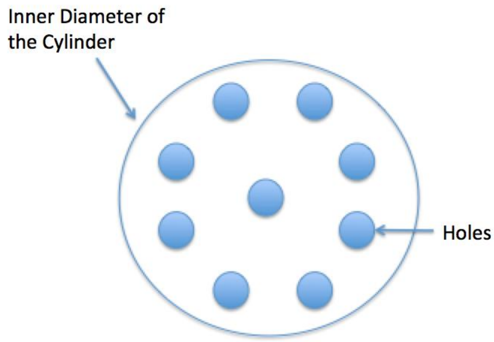

Figure 4: Hole arrangement inside the acrylic base of the primary cylinder

- Using a self-drilling M3 screw, attach the rubber to the **top face** of the acrylic base.
- Using acrylic glue, glue the base of the primary cylinder to the primary cylinder. Ensure that the top face of the base is facing upwards such that the rubber is on the inside of the primary cylinder! Figure 3 provides a photo of the finished product.

2.2.2 Crankshaft

The crankshaft was by far the most difficult mechanism to manufacture. The main reason for this was that the crankshaft had to be extremely strong in order to provide enough force to raise the piston. Often, pieces became dislodged. We strongly discourage the use of glue in any capacity when manufacturing this part simply because glue is generally not strong enough for such an application. The crankshaft mechanism is divided into three main components: the disk, the connecting piece and the handle. Note that the handle assembly was very straightforward and is not mentioned here. Important points relating to the manufacturing of each of these components are explained below.

- **The Disk:**

When designing the disk, there two things needed to be considered. Firstly, an appropriate diameter for the main disk had to be selected. The diameter of the disk will depend heavily on the length of the primary cylinder. Generally speaking, the disk diameter should be about 5 cm smaller than the height of the cylinder in order to prevent the piston from coming into contact with the top or bottom of the primary cylinder.

The other main design choice that needed to be considered when designing the disk was the following: what is the best way to attach the disk to the main axis? At first, the disk was press fit onto the main axis, however this did not prove to be strong enough. Eventually, a second, supporting piece of acrylic was cut and glued to the main disk. This supporting piece included two holes on its side that allowed two screws to pass through and clamp the axis in place. Moreover, the supporting piece had a large hole in its centre that allowed the main axis to pass through. This design was strong enough and very effective. An important design decision that was considered here was the thickness of the supporting piece. It needs to be thick enough that it will not crack when a small screw is screwed in. Generally, as long as the acrylic is thicker than 8mm and the screw is no larger than an M3, there should be no problems.

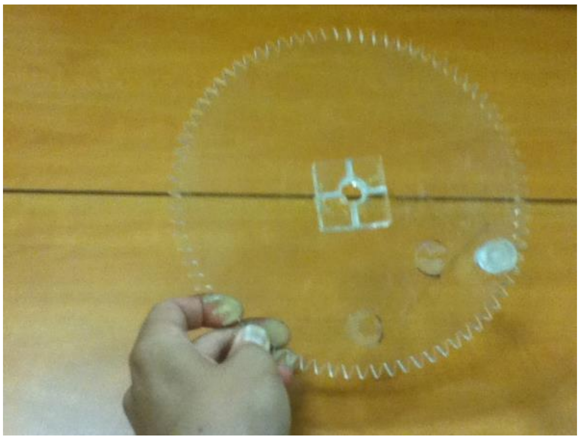

Figure 5: Crankshaft disk

- **The Connecting Piece:**
  The connecting piece refers to the long acrylic bar that connects the piston and the main disk. Two important design decisions had to be considered when manufacturing the connecting piece. Firstly, a reliable method of attaching the connecting piece to the main disk had to be developed. At first, a small tab was attached on the edge of the main disk using acrylic glue. Unfortunately, after testing, we found that the acrylic glue was simply not strong enough to withstand the force required to operate the pump. A hole was then drilled through the disk so that the connecting tab could be mounted using a screw. This design was much more reliable.

  The other main design decision had to do with attaching the connecting piece to the piston. A small hook was screwed in to the end of the wooden piston. Next, a small hole was added to the bottom of the connecting piece. This hole was larger than the diameter of the hook in order to allow the connecting piece to be removed easily. The connecting piece would then latch on to the piston. This design was effective and so no further changes were made.

2.3 Standard Operating Procedure

The steps below outline a specific procedure for the use of the water pump:

1. Remove the lid from the primary cylinder and unscrew the tab on the crankshaft disk.
2. Remove the piston from the primary cylinder.
3. Lubricate the primary cylinder by applying a small amount of oil and grease around the inside of the cylinder.
4. Reinsert the piston into the cylinder and attach the lid.
5. Reattach the tab to the crankshaft disk.
6. Fill up the container with water. Only fill the container approximately halfway to prevent spilling
7. Place the pump on top of the container so that the primary cylinder sits inside the container. The base should sit directly on top of the container. If this is done correctly, the pump should be stable.
8. With one hand, grip the crankshaft and turn. The direction of the turning is immaterial.
9. Continue turning the disk until the water in the container has been exhausted. (**Note:** it will take one or two turns before the pump starts to dispense water. This is normal – the pump simply needs time to push water all the way through the secondary cylinder and exit tubing).
10. Continue turning the disk until all the water inside the pump has been exhausted. This is a crucial step. Not emptying the pump after use can make the metal screws, which are used to mount the valves, rust.

2.4 Potential Improvements

The water pump operates quite effectively. The valves are reliable and all the connections seem to be strong enough to allow the pump to operate properly. That being said, a couple of improvements could still be made to the design in the future.

The main issue with the current design was that there is too much friction between the piston and the primary cylinder. The rubber that was available in the lab was not appropriate for this application as it was too soft. The sealing mechanism was changed so that it used an o-ring mechanism with a tougher, nitrile base rubber, but that change only marginally reduced the friction. More research should be done in order to determine what rubber would be best for this particular application.

Moreover, the authors would suggest replacing the silicone rubber used in the valves with a different, harder type of rubber. This should also reduce the amount of friction in the pump and make the pump easier to use.

Finally, the axis on the crankshaft is currently very wobbly, although it does allow the crankshaft to turn well enough. The reason for this is that the hole that was cut into the acrylic piece that supports the entire crankshaft was too large. Rather than replace the entire supporting piece, we would recommend cutting two thin pieces of acrylic that could be glued on either side of the supporting piece. These acrylic pieces should have a hole in the centre that is only slightly larger than the diameter of the axis. This change will prevent the crankshaft from wobbling.

3.0 Induction Coils

Induction coils are an extremely useful tool in science and engineering. Spark production, which is what induction coils are used for, allowed for the invention of the combustion engine, which powers most vehicles today.

Induction coils generally involve three main components:

1. **Interrupter mechanism**: The interrupter mechanism rapidly turns the primary circuit on and off. This cycling is crucial if the circuit is to function properly. Without the interrupter mechanism, no induction will occur.
2. **Primary Coils**: The primary coils are directly attached to the power source. Generally, the primary coils are made of thick wire in order to minimize the resistance and reduce energy loss. The primary coils should be wrapped around a ferromagnetic, iron core to increase the amount of induction in the coils.
3. **Secondary Coils**: The secondary coils are not connected to the power source. The secondary coils are generally made of very thin wire in order to maximize the inductance of the circuit. The secondary coils use the magnetic field generated by the primary coils to induce a very high voltage in the secondary circuit, creating a spark.

3.1 Overall Description

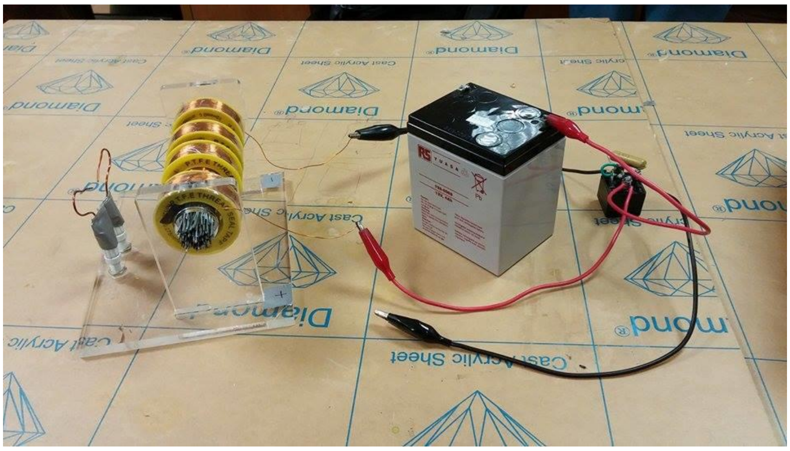

Figure 6: Prototyped Induction Coils

The induction coils that we made were manufactured so that the entire assembly was modular. In other words, the secondary coils were separated into four smaller reels. These reels were then connected together using solder and electrical tape. The advantage of this design was that one could change the magnitude of the voltage inside the secondary circuit to suit their individual requirements by adding or removing reels from the assembly. The secondary coils were made out of 0.08mm thick wire and each reel contained approximately 13 000 coils.

The primary coil was manufactured out of much thicker wire. The diameter of the wire used to make the primary coil was 0.5mm**.** Approximately 215 turns were on the primary coil, making the coil approximately 11cm long. The coil was wrapped on a small acrylic tube (OD = 25mm), which insulated the iron core from the primary coil and also made it considerably easier to manufacture. The addition of the acrylic tube was crucial to the success of the design as it prevented the secondary coils from shorting to the iron core.

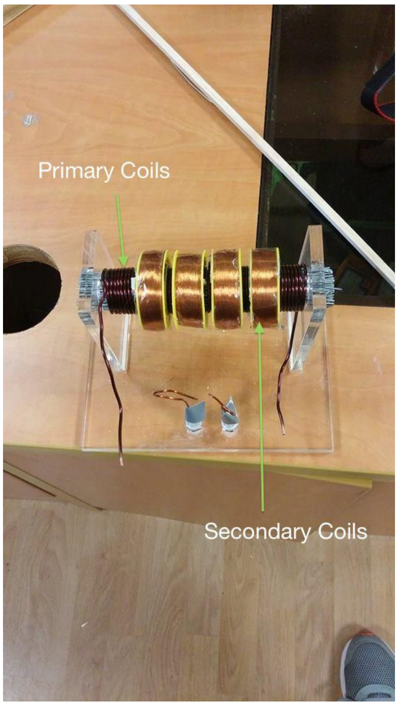

Figure 7: Primary and Secondary coils

In the circuit, a simple car relay circuit was used as the interrupter mechanism. This circuit was reliable and easy to use. The car relay used in the design was designed to function with 12V and had a maximum current rating of 30A. The car relay was designed by Multicomp and the part number was MC25115.

The coils were mounted on a compact acrylic base. The main reason acrylic was chosen here was because it was both transparent and readily available. Transparency was beneficial as it allowed observers to see all the different parts of the coils while the circuit was operating.

The iron core is made out of a number of a large number of short pieces of iron wire. Wire was used instead of a solid iron core in order to prevent eddy currents and reduce energy loss.

The coils operate using a 12V, 4Ah car battery. Weaker batteries will not work with our coils due to the relatively high resistance of the primary coils.

3.2 Manufacturing Process

3.2.1 Winding of the Primary Coil

The primary coil is typically wound with thicker wires, typically only involving tens or hundreds of number of turns. Because of the thickness of the wire, it could not be coiled using a machine and relied heavily on hand coiling. The process for winding the primary coil consisted of hand coiling a wire around a 25mm diameter acrylic tube.

The acrylic tube was very useful as it allowed the iron core to be inserted easily without damaging the primary coil. However, it is important to ensure that the walls of the acrylic tube are thin keep the as thick walls will distance the iron core from the primary. Another advantage of the acrylic tube is that it prevents any possible shorting between the secondary coils and the iron core. Originally, the acrylic tube was removed after winding. This did not work effectively as it often misshaped the primary coil.

Another crucial aspect of the primary coil is the thickness of wire. Originally, we used 2mm, however, this resulted in a very low resistance of the primary coil. When connected with a 12V car battery, too much current flowed through the primary circuit, overflowing the car relay. Later on, we changed the thickness to be about 0.5mm, which worked very well with the powerful 12V battery. That being said, weaker power sources were unable to power the circuit effectively. For example, regular 1.5V, D batteries connected in series only produced tiny sparks. The reason for this was that the 0.5mm wire resulted in too much resistance.

3.2.2 Winding of the Secondary Coils

Winding the secondary coils consumed the greatest amount of time for this project. As previously mentioned, the secondary coils were manufactured modularly. Teflon tape reels, purchased at a local hardware store, with the Teflon tape removed were used to mount the wire. These reels were affordable and easy to use. On one side of the reel, a hole was nailed through the wall of the reel such that the hole was located as close as possible to the center of the reel. This is where the wire was inserted. Once the reel was completely wound, the wire exited from the other side of the reel. It is important to maximize the distance between the entry and exit of the wires in the reel to prevent shorting.

Choosing the right thickness of the secondary coils is also a very important decision. The secondary coil requires tens of thousands of turns whereas the primary only requires tens to hundreds. In general, the wire must be thin. In our experiment, we ended up using the thinnest possible wire we had which was 0.08mm. This had its advantages because we were able to wind up to 12 000 turns on each reel. As a result, the inductance of the coils was high.

On the other hand, there are clear disadvantages to using an extremely thin wire. During coiling, thin wire is very easy to snap and reattaching the wire is a time-consuming process. It involves sanding down the enamel, tying the wires together, and finally taping them. Another issue is that thing wire creates a very high resistance, which will reduce the current throughout the secondary coil and possibly reduce the power of the emitted spark. For example, the resistance of the prototyped secondary coils was 20kΩ.

In this experiment, we used an old metal wire winding machine that was hand-powered. A teflon reel would be loaded onto the machine and spun as the machine is cranked. On the other side would be another reel containing the feeding wire. This reel should not be bound and must be allowed to spin freely. The machine required 2 people to operate it. One individual would use their finger or a pully support to guide the wire that is feeding into the reel. This allows for even distribution of wiring and prevents the wire from winding outside of the reel. The other individual will be doing the actual cranking of the machine.

A couple tips that were learned during the wiring process are presented below:

1. The speed of winding does not really affect the snapping of the wire. The wire often broke because of sudden jolts of motion – not high speeds. In other words, it is important to accelerate slowly when speeding up or slowing down the cranking speed. Being focused and concentrated is crucial in winding the wire at a constant speed.
2. Ensure that the person who is guiding the wire into the reels holds the wire well above the reel. This reduces the amount of tensile stress on the wire. Often, the wire would break when the person guiding the wire lowered his or her hand.

Originally, in order to connect the reels, the enamel was removed from the leads of the two reels being connected. Next, the wires were wound together and then sealed with electrical tape. This method was not reliable. Often the connection became loose and had to be redone. Even worse, often the wire leading into the reel would snap. This was a huge issue as the reel then became useless because it couldn't be connected.

To relegate both of these problems, a small amount of solder was placed on top of hole where the wire entered the reel. Next, the leads were connected using the soldering iron. Finally, the connection was insulated with electrical tape. This design was very effective as the connections were more reliable. Moreover, if the wires did break, the reel could simply be resoldered instead of having to be rewound completely.

3.3 Standard Operating Procedure

The procedure below explains the steps required to safely operate the induction coils. Because of the strength of the battery, it is crucial that the user adhere to this procedure carefully in order to prevent any safety mishaps.

1. Ensure the battery is not attached to the car relay
2. Attach either one of the red alligator clips on the car relay to the side of the coils marked "+"
3. Attach the black alligator clip that is wrapped in a piece of duct tape to the side of the coils marked "-"
4. Attach the other red alligator clip to the positive terminal on the battery

5. Touch the black alligator clip to the negative terminal of the battery. Sparks will begin to be produced in the secondary circuit. If you see any sparks outside of the secondary circuit, remove the wire from the battery immediately. Additionally, if you don't see any sparks, remove the wire immediately as that means something has shorted or the circuit is not connected properly.

3.4 Potential Improvements

The main improvement that could be made to the induction coils would be to change the diameter of the wires. As previously mentioned, the wire used in the primary coils was too thin for this particular application. As a result, the resistance of the primary coils was too high. We would recommend using wire that is 1.0mm thick for the primary coils.

Similarly, we would recommend using thicker wire for the secondary coils as well. The main reason for this is that using thicker wire would greatly speed up the manufacturing process, as it would prevent the wire from breaking as often. Additionally, using thicker wire would reduce the resistance of the secondary coils, making stronger sparks. We would recommend using wire that is approximately 0.16mm thick for the secondary coils.

4.0 Marble and test tube Stirling Engine

Stirling engines are engines that are powered exclusively by a temperature differential. Another key part attribute of Stirling engines is that the working fluid is always in a gaseous state [1]. This is not always the case with other combustion engines.

4.1 Overall Description

The design that was chosen for this project was made using marbles, a test tube and a syringe. The design was extremely simple, but difficult to configure properly. A list of each of the components is provided below as well as a description of the role played by each component:

- Test Tube: The test tube played the role of the cylinder. It housed the working fluid, air, and also contained the displacer (the marbles). The test tube was sealed with a rubber stopper in order to ensure that air would not escape during engine operation.
- Marbles: The marbles played

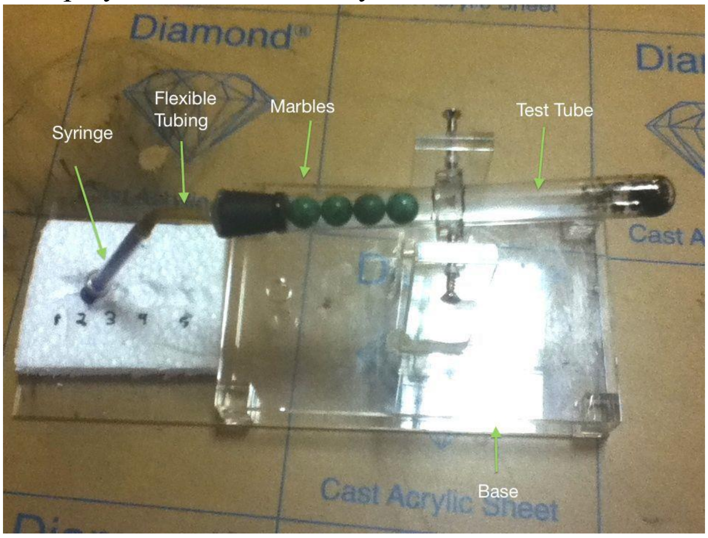

Figure 8: Prototyped Stirling engine

the role of the displacer. The marbles, which were slightly smaller than the inner diameter of the test tube, were placed inside the test tube and allowed to move freely. While the engine was running, the marbles would displace hot air to the front of the test tube, where it could cool down and recompress. The marbles' mass also forced the test tube to pivot about its axis, thus continuing the engine's motion.

- Syringe: The syringe provided the mechanical force required to push the test tube up and cause the test tube to start moving. As the air heated, it would expand, forcing the syringe to extend. This mechanical motion was what drove the engine. It was connected to the test tube with a small, flexible, rubber tube.
- Base: The base mounted all the components. It allowed the test tube to pivot freely and also provided the syringe with a platform on which to sit on. The material used for the base was acrylic and the syringe rested on a small Styrofoam platform.

4.2 Manufacturing Process

The design of the marble Sterling Engine is relatively simple. The materials used were acrylic, a 16 mm test tube, 1 mL glass syringe, flexible tubing, rubber stopper, marbles/beads, Styrofoam and candles. It is important to choose the syringe as glass because plastic syringes generate large amounts of friction and require a larger amount of force for motion to occur. The rubber stopper should fit tightly inside the test tube making it as airtight as possible. The tubing should be chosen such that it is airtight when fitted onto the syringe. The diameter of the marbles should be slightly smaller than the inner diameter of the test tube in order to allow air to flow past them. They should also be somewhat heat resistant.

The first important consideration when designing the stand of the engine is to allow the test tube to freely rotate. This was done by tightly inserting the test tube onto a small acrylic cylinder. Two screws were inserted on the sides of the acrylic cylinder and were held in place by two pillars. These pillars were glued onto an acrylic slab. This assembly allowed the test tube to rotate freely.

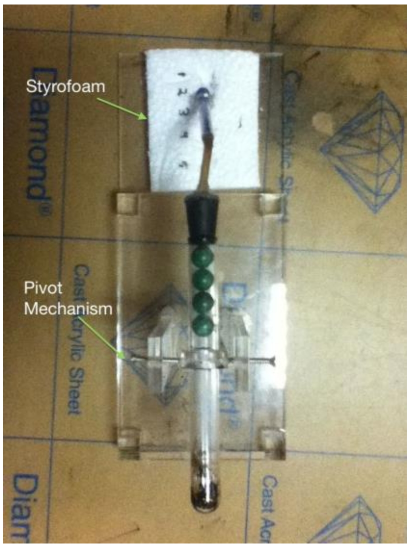

Figure 9: Prototyped Stirling engine - top view

The next step was to create a hole inside the rubber stopper and attach the tubing. It is extremely crucial that all components of the engine be airtight. For this reason, we used hot glue to attach the tubing to the stopper. Hot glue was used because it prevents air leakages. Moreover, most other adhesives generally do not work well on rubbery materials.

The Styrofoam is placed on the end of the acrylic base, which faces the open end of the test tube. Making holes in the Styrofoam allowed the syringe to stay at an appropriate resting position. The syringe should generally be kept straight up but at a slight angle towards the test tube. Also, it is important to note that to reduce friction inside the syringe, you need to move the piston up and down for some time. This must be done every time before the engine is started.

4.3 Standard Operating Procedure

The standard operating procedure below details exactly how to assemble the motor and run it. Ensure that all steps are followed carefully. Although the motor works reliably when it is set up properly, it will not work at all if it is not assembled properly.

1. Place a small amount of steel wool inside the test tube. The steel wool is present simply to protect the test tube from the impact of the marbles.
2. Place 4 green marbles into the test tube.
3. Slide the acrylic ring onto the test tube and push it upwards until the ring is in between the two marked lines on the tube.
4. Hold the test tube in between the two stands on the base. Ensure that the two holes drilled into the acrylic ring are directly facing the two holes in the stand.
5. Using a screwdriver and an 8-32 self-drilling screw, insert the screw through the hole in the stand and screw it into the acrylic ring. Repeat this step on both sides of the test tube. If done correctly, the tube should rotate freely.
6. Stick the stopper into the test tube. Ensure that it is airtight.
7. Move the piston up and down inside the syringe until the friction inside the syringe is brought to a minimum. This is a crucial step – the engine will not work if the syringe gets stuck.
8. Insert the syringe to the other end of the tube. While inserting, ensure that the piston is pushed all the way to the front of the syringe.
9. Test the apparatus to ensure that it is airtight. To do this, gently pull the stopper inside the syringe and then let go. If the piston returns to its original position, the apparatus is airtight and you can proceed to step 10. If not, check all connections inside the apparatus to ensure nothing is loose. If nothing appears to be loose, it is likely that the connection between the tube and the stopper needs to be re-glued with hot glue.
10. Rest the piston of the syringe in the hole marked “2” on the Styrofoam piece.
11. Light a small candle
12. Place the candle directly underneath the test tube. If the candle is very short, prop it up a little bit so that the flame is closer to the test tube.
13. After approximately 1 minute of heating up, the engine should begin to run.

4.4 Potential Improvements

This experiment proved to me the most troublesome for us even though it was relatively simple to build. The problem is that there are so many factors that determine the success of the engine. For example, the size of the test tube, size of the marbles, size of the syringe, material for the tubing, and heat source intensity affect the engine's performance. As a result, finding the perfect combination of materials was difficult.

Although the engine worked quite well in the end, one improvement that can be made is to adjust the size of the test tube. We used both a high level burner and candles for our experiment. With the burner, we noticed that movement was much more controlled and in rhythm. However, with the candle, movement was very rapid and less rhythmic. Since one of the requirements of this project was to use a small candle to operate the engine, the heat source cannot be changed. That said, the size of the test tube could be reduced. That will of course require smaller marbles as well. Overall, this will reduce the downwards force on the syringe making the engine more efficient. However, if the test tube is made too small, then there will not be enough air to expand and the engine will not work. The goal is to find the most appropriate test tube size for this application.

References

[1] A. J. Organ, Stirling Cycle Engines: inner workings and design, Chichester: Wiley, 2014.

[2] [Online]. Available: http://www.mlahanas.de/Greeks/images/ctesib1.jpg. [Accessed 14 July 2016].