Stirling Engine Project Final Report

ME 449 – Redesign and Prototype Fabrication [Plan]

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Team E

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Introduction

A Stirling engine is a heat engine whose operation relies on the cyclic compression and expansion of air (or another gas) at different temperatures, resulting in the net conversion of thermal energy to mechanical work [1]. Over the course of this semester, we worked on assembling a gamma style Stirling engine. The unique feature of this type of engine is that it can run on low temperature differentials. If executed properly, it can operate under a 7 [C] temperature difference. In the first half of the semester, we worked on building and assembling our gamma style Stirling engine based on the dimensions provided by Professor Frank Pfefferkorn in class. In the second half, however, we worked on enhancing our engine based on a set of design requirements, which are detailed in this report.

Design Requirements

Once we finished manufacturing the required parts, we assembled our Stirling engine. This initial assembly serves as our baseline and marks the start of the redesign stage. The first step in the redesigning process is to identify the design requirements. We brainstormed and prepared a list of design requirements, which are ranked in Table 1.

Table 1: Design requirements ranked from most to least important

Requirement #	Name	Importance [1-5]
1	Speed (Performance)	5
2	Build Quality	4
3	Aesthetics	3

The first and most important design requirement which we will tackle is speed (or performance). We prioritized it because it is the first parameter consumers look at. Although some products might look better, the customer will always go for the one that is more effective. The design requirement which is ranked second is the Build Quality, because it is crucial to deliver a product that lasts. Indeed, if a product is characterized by having a poor quality, it might perform well in the short run. However, sales will quickly decline as customers switch to alternative options. Finally, aesthetics play a critical role in the design process, since it makes the product appealing to customers. However, as engineers, we are generally less concerned with aesthetics, as we tend to focus more of performance and build quality. Therefore, this parameter is given the lowest weight.

Objectives / Goals

Once our design requirements were laid out, the next step is to set the objectives and goals for each requirement. The ultimate goal would be to achieve superior results in every category. However, due to time restrictions, we were only able to improve so much. This led us to develop the set of tangible objectives, which are given in Table 2.

Table 2: Objective / Goals for each design requirement

Requirement #	Name	Description	Goal
1	Speed (Performance)	Measure the number of cycles the work cylinder completes in one minute	200 [rev/min or RPM]
2	Build Quality	Grade the Stirling engine based on how reliable and sturdy it looks and feels	9 on a scale [1-10]
3	Aesthetics	Grade the Stirling engine based on good it looks	8 on a scale [1-10]

Before testing our initial benchmark Stirling engine, we set a goal of 30 [rev/min] because we were not sure how fast our initial engine would perform. Once we tested it, we realized that our base case already exceeded our goal of 30 [rev/min], which drove us to reconsider our initial goal. Consequently, since our benchmark engine ran at 150 [rev/min], we decided that an achievable target would be to improve its performance by 33%, which translates to 200 [rev/min]. As for the aesthetics and build quality goals, our benchmark engine did not meet our initial expectations. Therefore, we decided to keep our initial objectives of 9 out of 10 for build quality and 8 out of 10 for aesthetics.

Prototype Changes/Improvements

With a clear set of requirements and objectives in mind, we move on to the prototype changes / improvements. In order to improve our design requirements, the team focused on four primary areas, highlighted as follows:

1. Improve the contact between the fasteners and linkages.
2. Create a better seal for the displacer chamber.
3. Limit the heat transfer between the top and bottom plate.
4. Replace the working fluid in the displacer chamber.
5. Improve the aesthetics.

1. Improve the contact between the fasteners and linkages

During the testing stage of our benchmark Stirling engine, we noticed a clicking noise coming from the linkage and hub on both the crankshaft and the displacer hub. To improve the contact between the hub and linkage, the team devised a plan to add nylon spacers. Steel – Nylon has a lower friction coefficient compared to Steel – Steel, as shown in Table 3.

Table 3: Coefficient of friction comparison

	Coefficient of friction [-]

Steel – Steel	0.8
Steel – Nylon [2]	0.4

This lower friction coefficient contributes to a decrease in the force of friction, as seen in Equation 1.

$$F_{friction,static} = \mu_{static} \times N \quad (1)$$

Where μ_{static} is the coefficient of friction [-], and N is the normal force acting on the linkage [N]. The detailed calculations can be found in Appendix A and the results are recorded in Table 4.

Table 4: Force of friction calculation result

Location	Weight [g]	Force of Friction [N] (S-S)	Force of Friction [N] (S-N)
Flywheel Hub	4.2262	0.033	0.017
Crankshaft Hub	16.1659	0.127	0.063

Throughout the testing stage of our initial Stirling engine, we noticed that linkage would either loosen the fastener or completely come off due to its excess motion. In order to secure the linkage, we machined a groove channel along the nylon displacer. A sketch portraying this concept and the implementation site of the nylon displacer can be seen in Figure 1.

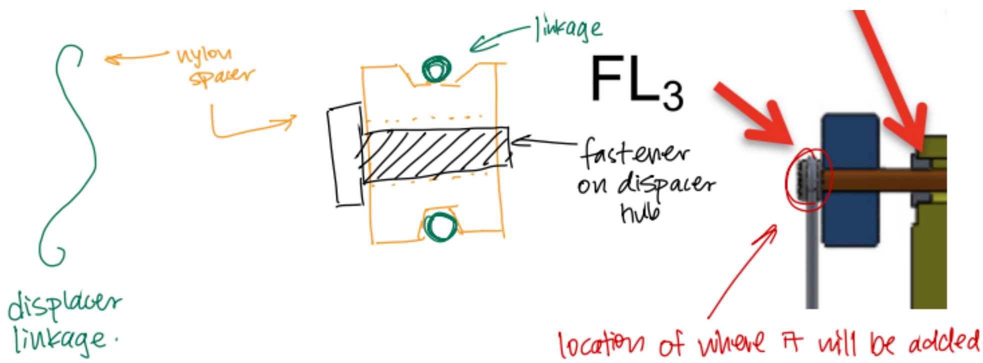

Figure 1: Sketches showing the groove channel and the implementation site of the nylon displacer

The third and final motive is to make our redesigned Stirling engine more aesthetically pleasing. When people think of aesthetics, the first thing that comes to mind are appearances; however, sound plays an important role as well. Decreasing the unnecessary motion of the linkages should decrease the clicking noise resulting from the metal-to-metal contact.

2. Create a better seal for the displacer chamber

The working fluid is the driving mechanism of our Stirling engine. The ideal cycle of a Stirling engine is represented in Figure 2, with an example of a simulated P-V diagram and an experimental P-V diagram (note: this is only used as a reference).

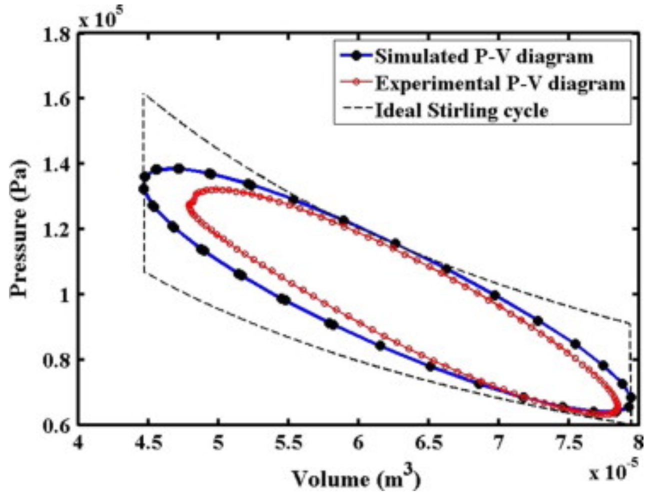

Figure 2: Graph showing the ideal Stirling cycle, simulated P-V diagram, and the experimental P-V diagram [3]

The work done by the Stirling engine can be calculated using Equation 2.

$$W = \int P \, dV \tag{2}$$

Where P is the pressure [Pa] and V is the volume [m^3].

Any leaks from the displacer cylinder chamber would lead to a decrease in the cooling capability of the bottom plate. As a result, we would expect to see a temperature increase, which would in turn lead to a decrease in density. Subsequently, this drop in density would lead to a smaller volume difference, area and work. When we performed the smoke test on our benchmark Stirling engine, we noticed a significant leak through the displacer driver cylinder, as shown in Figure 3.

Figure 3: Image showing the leak through the displacer driver cylinder

To address this leak, we decided to machine a new bushing that would give a tighter tolerance. We measured the outer diameter of the displacer rod and added 0.001 inches to it. This gave us the inner diameter of the new bushing.

3. Limit the heat transfer between the top and bottom plate

In order to limit the heat transfer from the top to the bottom plate, the team decided to add plastic washers beneath the 6-32 faster head. Plastics are good insulators, since they have a lower heat conductivity compared to metals. This can be observed in Table 5.

Table 5: Thermal conductivity values

	Stainless Steel	**Polyethylene**
Thermal conductivity (k) [W/m-K]	14.6	0.42

Adding the plastic washers beneath the bolts would cause their thermal resistances to be connected in series, as shown in Figure 4.

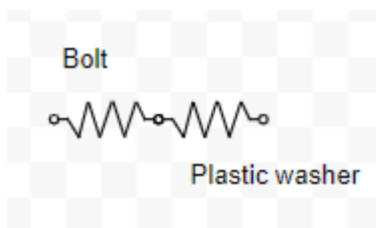

Figure 4: Thermal resistance circuit

The thermal resistance and heat loss rate can be calculated using Equations 3 and 4, respectively.

$$R = \frac{L}{K \times A_c} \quad (3)$$

$$\dot{q} = \frac{\Delta T}{R} \quad (4)$$

Where L is the functional length [m], k is the thermal conductivity [W/m-K], A_c is the cross-sectional area [m^2], and ΔT is the temperature difference between the hot and cold side [K].

Since the thermal resistances are in series, we can add both resistances together. From this, we deduced that adding the plastic washers should increase our total resistance, which would in turn decrease the rate of heat loss from our system. The detailed calculations can be found in Appendix B, and the results are highlighted in Table 6.

Table 6: Net-work results

	Initial Design	Redesign (with washers)
Net Work (W_net) [J]	0.0225	0.2381

Based on our calculations, we were able to corroborate our theoretical analysis, since the washers resulted in a 0.2156 [J] (or 215 mJ) increase in power.

4. Replace the working fluid in the displacer chamber

To further improve the performance of the Stirling engine, we investigated the possibilities of replacing the working fluid with helium. Based on a research study performed by the University of Jordan, helium and hydrogen gas are viable replacement options since they have a higher heat-transfer capability compared to other fluids. A plot showing the variation of power as a function of temperature rate is shown in Figure 5 below.

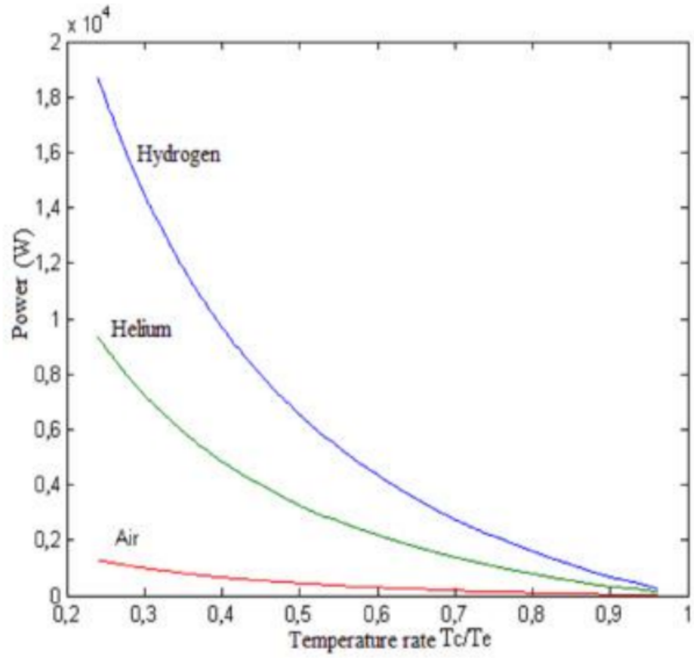

Figure 5: Variation of power as a function of temperature rate for different working fluids [4]

Based on Figure 5, we can see that hydrogen has the highest power output in comparison to helium and air. However, since hydrogen is a highly flammable gas, we opted for helium since it is an inert gas. Detailed calculations and equations can be found in reference [4]. Moreover, compared to air, the power output of helium is approximately 5 times higher, making it an ideal choice for our engine. In order to implement this change, the team decided to purchase a small tank of helium gas and fill the chamber through the NPT threaded hole on the bottom plate.

5. Improve the aesthetics

In order to improve the appearance of our Stirling engine, multiple steps were taken. We started by remaking our flywheel. The inspiration behind our updated design was smoothness and minimalism. In addition, we worked on giving all visible parts a nice finish. If a part had major dents or scratches, we re-machined it using the appropriate tooling. After the completion of the re-machining process, we moved on to the polishing stage. This consisted of filing the surface then sanding it down using grit paper (starting with a coarse grade all the way down to a fine grade sandpaper). Finally, we ended the process by applying a coat of aluminum polish. Before and after images are referenced in Appendix C and D.

Testing Plan and Results

In order to test out how successful our redesigns were, we laid out the following testing plan:

1. Speed Test
2. Smoke Test
3. Temperature Test
4. Survey for Aesthetics/Build Quality

The first test we decided to tackle was the RPM Test. For the latter, all we needed was a metronome app, a bucket of ice and our Stirling engine. This test starts off by placing the Stirling engine in the ice bath for a 180 [s], before measuring how many revolutions the work cylinder undergoes in 1 [min], measured using the metronome app (which can be downloaded on any smartphone). Another requirement is that the Stirling engine has to be started within 120 [s] from its initial contact with the ice bath so that it has enough time to reach steady state conditions and to give us an accurate reading. The results of the RPM test are tabulated below in Table 6.

Table 7: Speed test results

	Initial Setup	**Redesign**
Speed [rev/min]	150	250

In the initial run of our Striling engine, we measure a 150 [rev/min or RPM]. After our redesign, we were able to increase the speed of our engine by 66.67%, as we were able to achieve a 250 [rev/min] speed.

The second test we conducted is dedicated to identifying any leaks that may be present in our Stirling engine. This test consists of feeding the displacer cylinder chamber with smoke from a vape using a straw. After the smoke is successfully transferred, we place the engine on an ice bath for it to run. Once the engine is up and running, we monitor it for the presence of any smoke leaking from the displacer cylinder chamber. Ideally, we should have a perfect seal and the smoke should remain trapped inside. However, when we ran the test with our initial setup, we noticed a significant leak through the displacer drive cylinder (part 6), primarily the bushing. After we re-machined the bushing with a tighter tolerance, we re-ran the test and could not find any significant leaks from our system, as shown in Figure 6.

Figure 6: Smoke test with the new bushing

Unfortunately, due to time restraints, we were not able to conduct the temperature test in time, but we plan on performing it soon. The aim of this test is to monitor the effects of the plastic washers in limiting the heat transfer from the bottom to the top plate. The way we plan on performing this test is by placing our Stirling engine in the ice bath for 180 [s] and measure the temperature of the top plate. Then we plan on repeating this process with the plastic washers inserted between the bolts and the top plate. Initially we planned on using an infrared thermal gun thermometer to measure the temperature difference. However, after performing some research, we agreed that such thermometers have a low resolution, thus making them inaccurate since we expect a small temperature change. In order to achieve a better accuracy, we plan on using a type-T thermocouple.

The fourth and final test we conducted was the survey in order to judge the success of our redesigns. To perform this test, we asked members of our 449 class to rate our aesthetics and build quality on a scale of [0-10], with 0 being the lowest score and 10 being the highest. This survey was completely anonymous as Professor Pfefferkorn collected the results. Based on the feedback received from our 18 classmates, our final scores are recorded in Table 8.

Table 8: Aesthetics and build quality survey results

	Initial Design	**Redesign**

Aesthetics [-]	7.53	8.89
Build Quality [-]	8	9.22

We received an Aesthetics score of 7.53 [-] and a Build Quality score of 8 [-] for our initial design. On the other hand, through our redesigns, we were able to improve our Aesthetics and Build Quality scores to 8.89 [-] and 9.22 [-], respectively.

Summary

During this semester, we manufactured, assembled and modified a gamma style Stirling engine. Throughout the redesign stage, we researched and investigated multiple sources of losses in our system. Based on our analysis, we revamped and added multiple components starting with the linkage hub moving to the plastic washers, displacer cylinder bushing, and finally the working fluid inside the displacer cylinder chamber. In order to judge how successful our redesign stage was, we conducted four main tests. The speed, smoke and temperature tests enabled us to quantitatively analyze our improvements. On the other hand, the aesthetics and build quality survey allowed us to rate our enhancements from a qualitative perspective. Although there is one more test we plan on performing (temperature test), it is safe to say that our redesigns were a success overall, since we were able to improve all our design requirements.

Acknowledgments

For this Stirling engine project, we would like to acknowledge and thank our instructor Professor Frank Pfefferkorn, our TA Ms. Aishwarya Deshpande, and finally all the TEAM Lab staff members for all the help and advice they offered throughout the entirety of this semester.

References

[1] “Stirling engine,” *IFISC*. [Online]. Available: https://ifisc.uib-csic.es/users/raul/CURSOS/TERMO/Stirling%20engine.pdf. [Accessed: 02-May-2021].

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Appendix A

```
"Known"
mu_s_s = 0.8
mu_s_n = 0.4
flywheel_hub_m = 4.2262 [g]*convert(g,kg)
crankshaft_hub_m = 16.1659 [g]*convert(g,kg)

"Force of Friction"
F_s_s[1] = mu_s_s*g#*flywheel_hub_m
F_s_s[2] = mu_s_s*g#*crankshaft_hub_m
F_s_n[1] = mu_s_n*g#*flywheel_hub_m
F_s_n[2] = mu_s_n*g#*crankshaft_hub_m
```

Known

$\mu_{s,s} = 0.8$

$\mu_{s,n} = 0.4$

$flywheel_{hub,m} = 4.2262 \ [g] \cdot \left| 0.001 \cdot \frac{kg}{g} \right|$

$crankshaft_{hub,m} = 16.1659 \ [g] \cdot \left| 0.001 \cdot \frac{kg}{g} \right|$

Force of Friction

$F_{s,s,1} = \mu_{s,s} \cdot 9.807 \ [m/s^2] \cdot flywheel_{hub,m}$

$F_{s,s,2} = \mu_{s,s} \cdot 9.807 \ [m/s^2] \cdot crankshaft_{hub,m}$

$F_{s,n,1} = \mu_{s,n} \cdot 9.807 \ [m/s^2] \cdot flywheel_{hub,m}$

$F_{s,n,2} = \mu_{s,n} \cdot 9.807 \ [m/s^2] \cdot crankshaft_{hub,m}$

SOLUTION

Unit Settings: SI C kPa kJ mass deg

$crankshaft_{hub,m} = 0.01617$ [kg]

$\mu_{s,n} = 0.4$ [-]

$flywheel_{hub,m} = 0.004226$ [kg]

$\mu_{s,s} = 0.8$ [-]

No unit problems were detected.

Arrays Table: Main

	$F_{s,n,i}$ [N]	$F_{s,s,i}$ [N]
1	0.01658	0.03316
2	0.06342	0.1268

Appendix B

```
"Michael Sukkar"
"Assumptions and variables"
time = 0.25 [s]                              "work is only done during a quarter of each cycle"
eta = 0.09 [-]
Q_dot_H = 1 [W]
TH = converttemp(C,K,20)                     "temperature of the room"
TC =converttemp(C,K,0)                       "temperature of the ice bath"
L = 38*convert(mm,m)                         "length of the bolt"
D = 3.5*convert(mm,m)                        "diameter of the bolt"
k = 14.6 [W/m-K]                             " thermal conductivity of the bolt"
k_plastic = 0.42 [W/m-K]                     "thermal conductivity of plastic washers"

"Equations"
Ac = pi#*D^2/4                               "cross sectional area of the bolt"
T_ave = 10 [C]                               "average temperature"
delta_T = TH - TC                            "temperature difference"
W_net = eta*Q_dot_H*time                     "Work equation derived in notes"
R_HL_bolt = L/(k*12*Ac)                      "thermal resistance across all the bolts"
q_dot = (TH-TC)/R_HL_bolt                    "calculate the heat traansfer rate across the bolts"
Q_bolt = time*q_dot                          "heat lost through the bolt during .25 s"
W_net = W_shaft - Q_bolt                     "finding the net work outcome using the shaft equation"
R_new = L/(k*12*Ac) + L/(k_plastic*12*Ac)    "thermal resistance across all the bolts with the plastic washers"
q_dot_new = (TH-TC)/R_new                    "calculate the heat traansfer rate across the bolts"
Q_bolt_new = time*q_dot_new                  "heat lost through the bolt during .25 s"
W_net_new = W_shaft - Q_bolt_new             "finding the new net work with the new top plate while eliminating the
bolts"
```

Michael Sukkar

Assumptions and variables

$time = 0.25$ [s] *work is only done during a quarter of each cycle*

$\eta = 0.09$ [-]

$\dot{Q}_H = 1$ [W]

$TH = \textbf{ConvertTemp}(C, K, 20)$ *temperature of the room*

$TC = \textbf{ConvertTemp}(C, K, 0)$ *temperature of the ice bath*

$L = 38 \cdot \left| 0.001 \cdot \frac{m}{mm} \right|$ *length of the bolt*

$D = 3.5 \cdot \left| 0.001 \cdot \frac{m}{mm} \right|$ *diameter of the bolt*

$k = 14.6$ [W/m-K] *thermal conductivity of the bolt*

$k_{plastic} = 0.42$ [W/m-K] *thermal conductivity of plastic washers*

Equations

$Ac = 3.142 \cdot \frac{D^2}{4}$ *cross sectional area of the bolt*

$T_{ave} = 10$ [C] *average temperature*

$\delta_T = TH - TC$ *temperature difference*

$W_{net} = \eta \cdot \dot{Q}_H \cdot time$ *Work equation derived in notes*

$R_{HL,bolt} = \frac{L}{k \cdot 12 \cdot Ac}$ *thermal resistance across all the bolts*

$\dot{q} = \frac{TH - TC}{R_{HL,bolt}}$ *calculate the heat traansfer rate across the bolts*

$Q_{bolt} = time \cdot \dot{q}$ *heat lost through the bolt during .25 s*

$W_{net} = W_{shaft} - Q_{bolt}$ *finding the net work outcome using the shaft equation*

$R_{new} = \frac{L}{k \cdot 12 \cdot Ac} + \frac{L}{k_{plastic} \cdot 12 \cdot Ac}$ *thermal resistance across all the bolts with the plastic washers*

$\dot{q}_{new} = \frac{TH - TC}{R_{new}}$ *calculate the heat traansfer rate across the bolts*

$Q_{bolt,new} = time \cdot \dot{q}_{new}$ *heat lost through the bolt during .25 s*

$W_{net,new} = W_{shaft} - Q_{bolt,new}$ *finding the new net work with the new top plate while eliminating the bolts*

SOLUTION

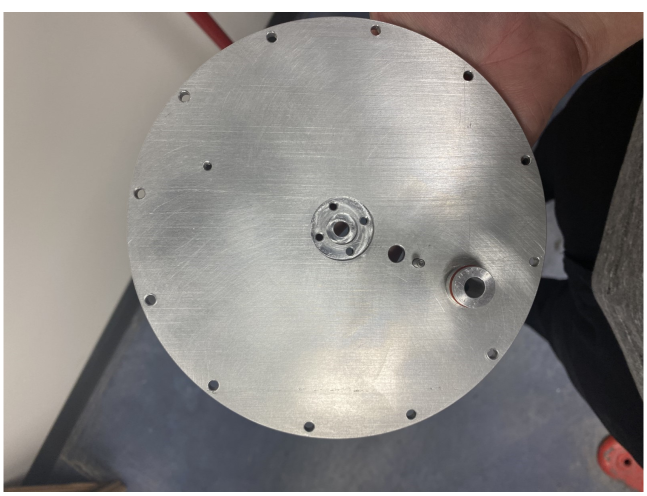
Unit Settings: SI C kPa J mass deg

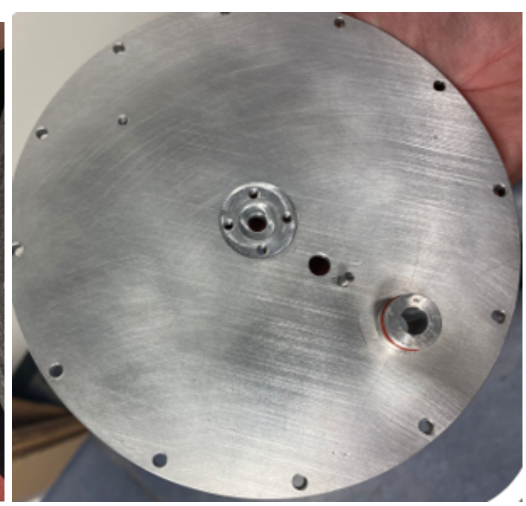
$Ac = 0.000009621$ [m^2]	$D = 0.0035$ [m]	$\delta_T = 20$ [K]
$\eta = 0.09$ [-]	$k = 14.6$ [W/m-K]	$k_{plastic} = 0.42$ [W/m-K]
$L = 0.038$ [m]	$Q_{bolt} = 0.2218$ [J]	$Q_{bolt,new} = 0.006202$ [J]
$\dot{q} = 0.8872$ [W]	$\dot{Q}_H = 1$ [W]	$\dot{q}_{new} = 0.02481$ [W]
$R_{HL,bolt} = 22.54$ [K/W]	$R_{new} = 806.2$ [K/W]	$TC = 273.1$ [K]
$TH = 293.2$ [K]	$time = 0.25$ [s]	$T_{ave} = 10$ [C]
$W_{net} = 0.0225$ [J]	$W_{net,new} = 0.2381$ [J]	$W_{shaft} = 0.2443$ [J]

No unit problems were detected.

Appendix C

Images of initial (benchmark) Stirling engine.





Appendix D

Images of redesigned Stirling engine.