Stirling Engine Project (March 09, 2013)

Years ago, I put significant effort into learning about and attempting to build a working DIY Stirling Engine. In other words, I wanted to build a homemade Stirling engine. My goal was to make a homemade Stirling engine of decent power (100 W or so) out of everyday materials you can purchase at Canadian Tire, Home Depot, or your local hardware store. A true DIY project, which just happens to be low-budget as well 😉 Now, given this self-imposed restriction, this was a huge challenge as I wanted to make something more than just a cute low-power model like the kind you see on YouTube 😉 So I went at it, and to be honest I never got an actual working engine, although I did get a lot of insight into how it works. And I did show that by powering the engine in reverse (as a heat pump), you can make a refrigerator out of it. More on that later.

First off, here is a picture of the homemade Stirling engine I made:

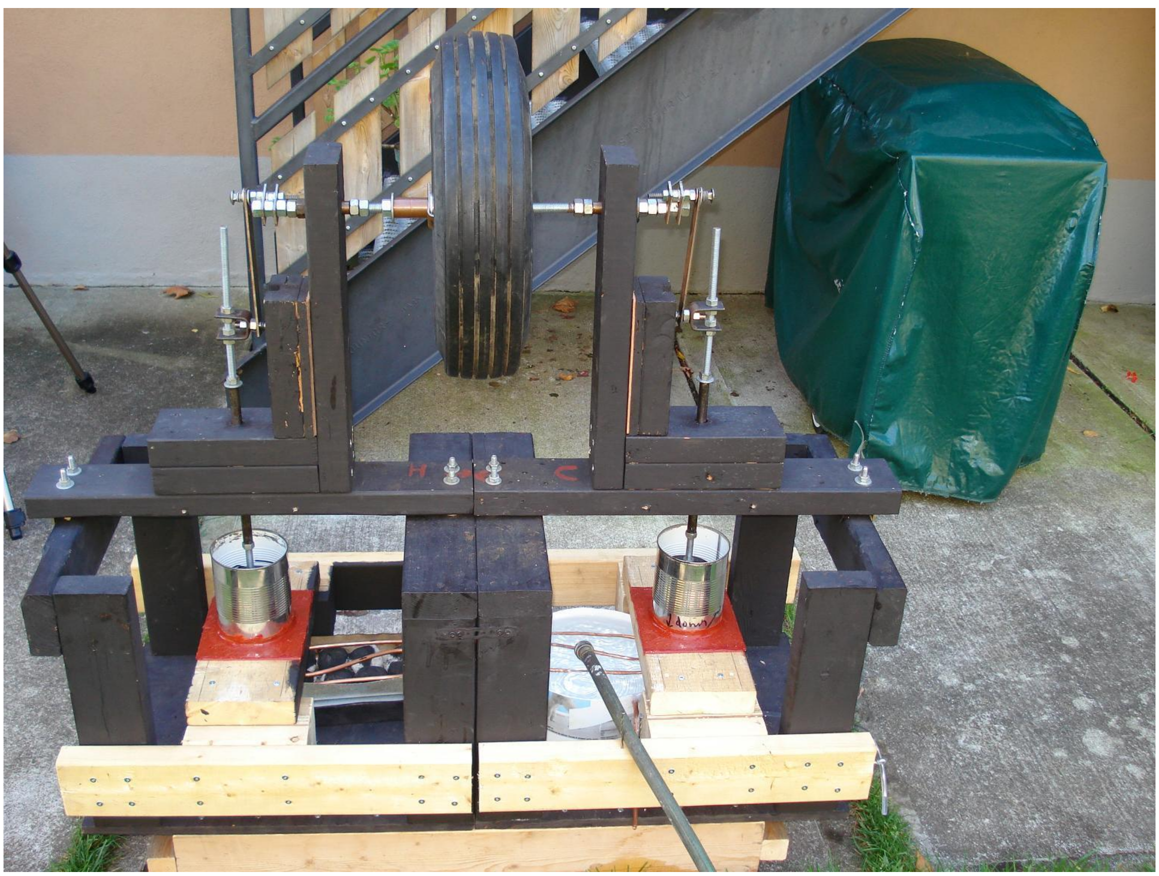

Figure 1

It's obviously made out of wood in large part. I chose wood because I happen to have a lot of it around and it's basically free, easy to work with and is often times strong enough to do the job. Now, I could have chosen to make the engine out of metal, but I don't have a machine shop or the necessary metal working tools. So I would have to get someone to machine the parts for me, and because it's a learning process there would be some trial and error involved. It can get pretty expensive if you know what I mean. So doing it the inexpensive way I set myself up for a basic understanding, so that when I do decide to make an engine out of metal it will be further along towards being functional. And believe me, these beasts are not as easy to make as one might think.

The above engine is an *alpha* configuration. I chose the alpha configuration because it is easiest for me to build given what I have to work with, and is simpler conceptually than the other types of configurations, which are known as *beta*, and *gamma* engines. You can find out more about them at the same Wikipedia link as before http://en.wikipedia.org/wiki/Stirling_engine and at this website, by Israel Urieli, which talks about the different mechanical configurations of Stirling engines: http://www.ent.ohiou.edu/~urieli/stirling/engines/engines.html.

The above engine was actually my fourth attempt at building a DIY Stirling Engine. As my understanding progressed it became obvious what I did wrong each time. Hindsight is 20/20 after all. And some things you can't know until you try and build it yourself. Hands on experience is the only way to get a good understanding of Stirling engine design.

And by the way, I won't bother showing you any of the work I did on those previous failed versions

Let's start off by dissecting what I did for this latest version.

The big thing was that I had to make the engine airtight. I learned early on that a key aspect of having a functioning, higher-power Stirling engine was being able to contain the working gas (which is air in my case) inside the engine with no (or very little) leakage. If you have an air leak you will lose power fast. The only way around that is to have an air compressor continuously pumping in air in order to maintain pressure. This was not an option for me, so I had to find a way to seal in the air using everyday DIY materials. So that means that using a piston with seals, plus bore (cut from a metal block), is out, as it's not DIY. So I opted to use a diaphragm of some sort, which would expand and compress.

To make the diaphragms I used pieces cut from silicone baking mats (purchased from the cookware section of Canadian Tire) and RTV high-temperature red silicone (also purchased at Canadian Tire) to attach them together. I found that RTV silicone forms a powerful and airtight bond with the baking mats. See Figure 2-5.

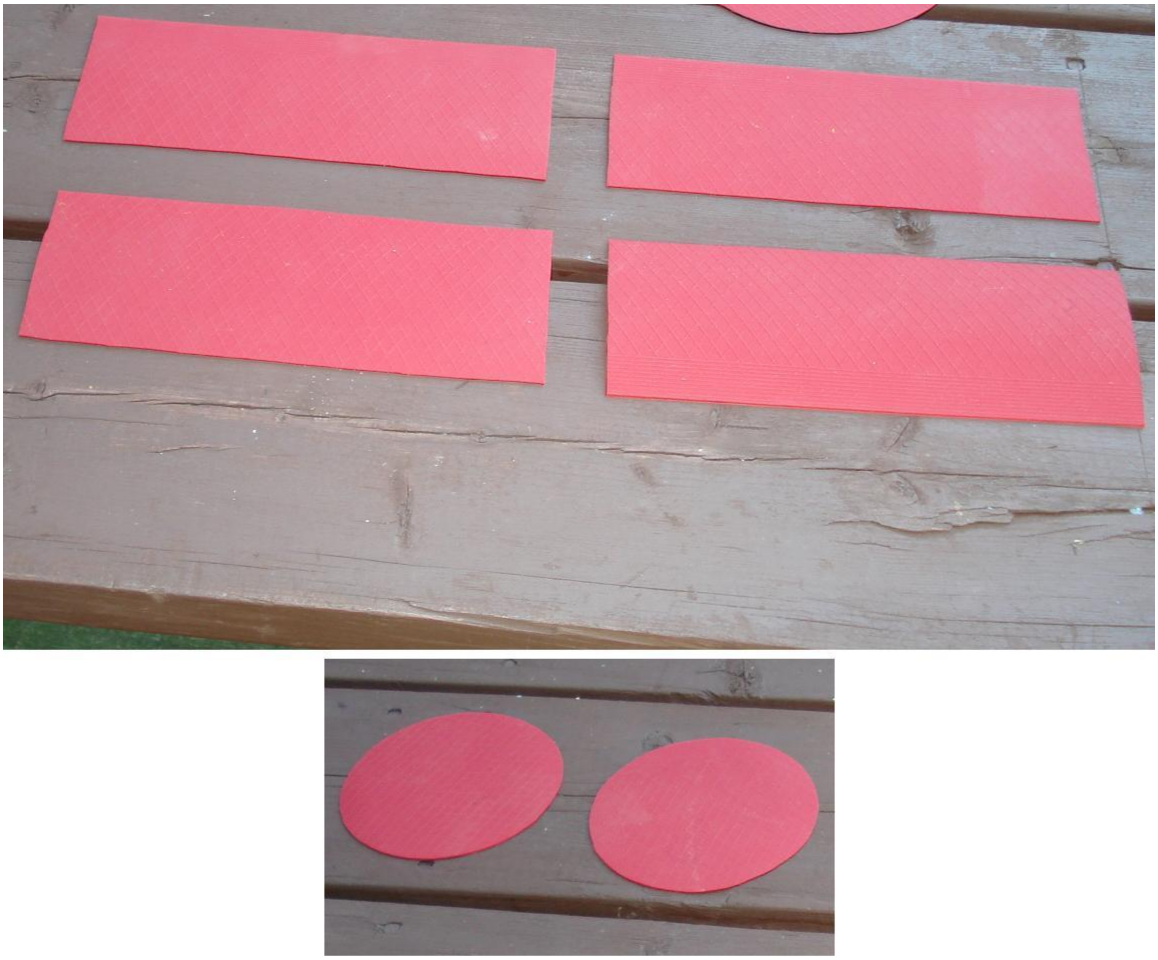

Figure 2

Figure 3

Figure 4

Figure 5: RTV high-temperature red silicone

From Figure 3 and 4 you can see that I coated the inside surfaces of the diaphragms with the RTV silicone. Since it can resist temperatures of up to 340 degrees Celsius (and the baking mat can resist up to 230 degrees) it acts as a kind of heat resistant barrier. I also coated the top surface of the diaphragm with silicone to help protect it from wear since this is where the piston sits and “pushes” against.

A key requirement in using the diaphragms is that the pressure inside the engine is always above atmospheric. This is a key part of the operating conditions. It means that at no point during the piston stroke can the diaphragms be “pulled” (since they can’t be “pulled”). They can only be “pushed”.

Before the diaphragms could be attached to the frame I needed to make a base. See Figure 6 and 7.

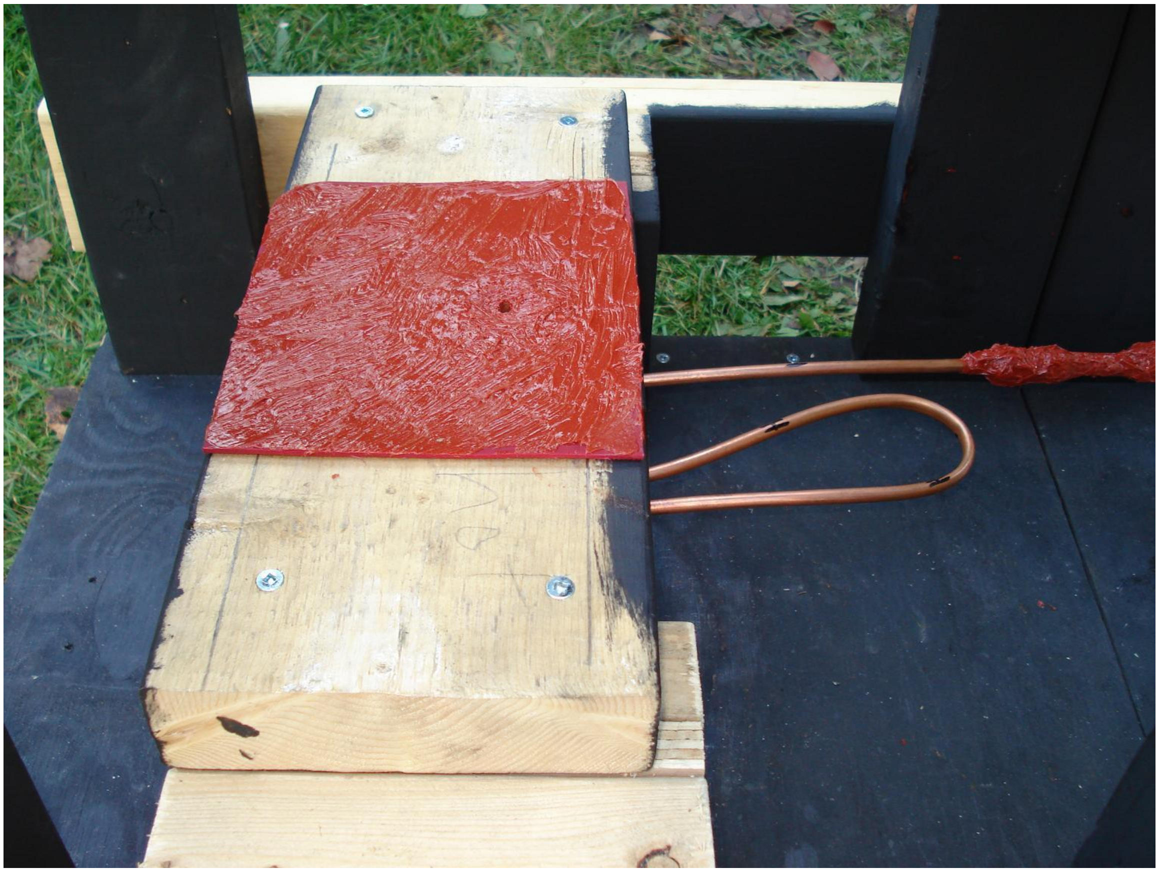

Figure 6: Hot engine side

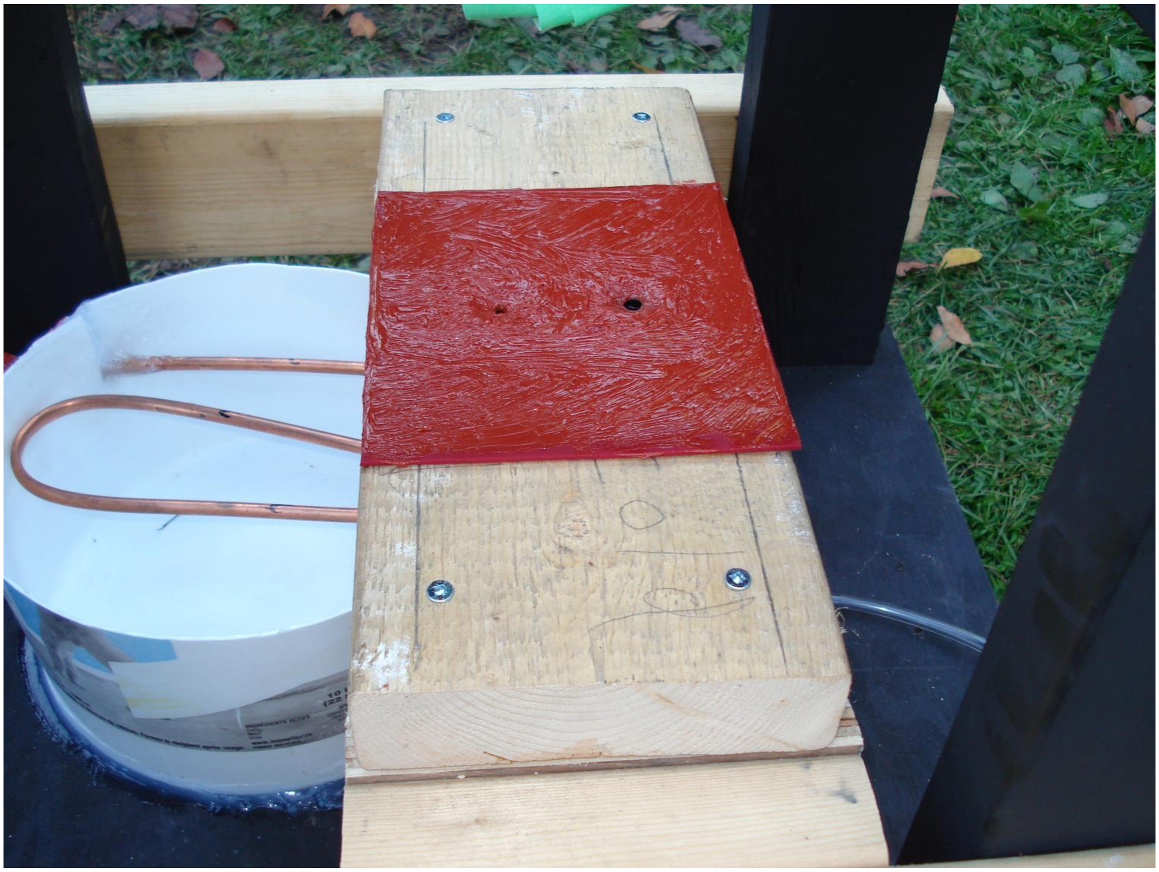

Figure 7: Cold engine side

The hot engine side is the part of the engine that receives heat, and the cold engine side is the part of the engine that is cooled. The heating and cooling takes place by way of heat exchangers which feed hot and cold air into the respective parts of the engine. See Figure 8.

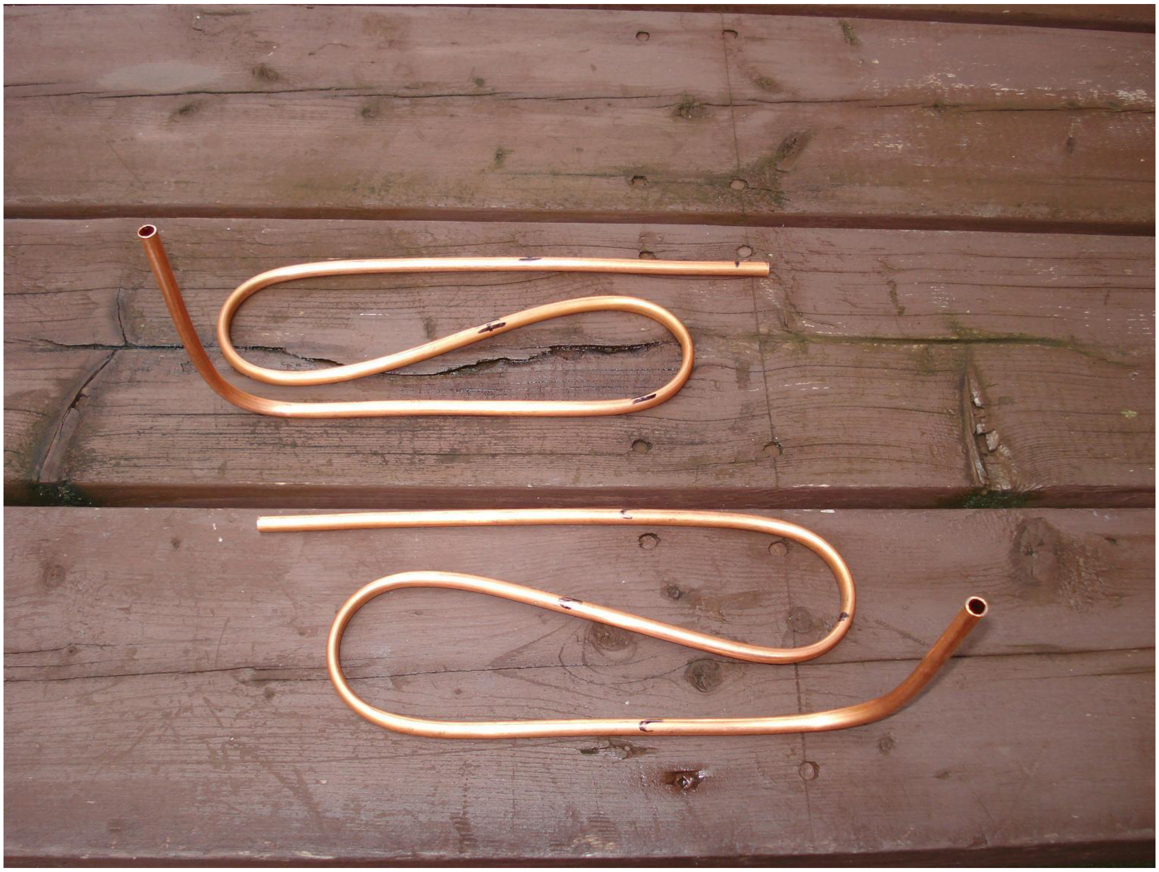

Figure 8

The heat exchangers are wound up lengths of 0.25 inch OD copper tube, roughly 80 cm in length, long enough to permit adequate heat exchange with the hot and cold sources which are in direct contact with them. I made them by bending the turns around a 1.5 inch dia. pipe, big enough to minimize flattening of the tube cross-section and avoid kinking. On the previous design I tried using much shorter copper tubes, flattened in order to increase the wetted perimeter relative to the cross-sectional area – in order to increase the heat transfer rate, in theory. This wasn't very effective despite the fact that the heat transfer formulas I used predicted a high heat transfer rate. So what I then did was experiment with different lengths of tube (not flattening them) by blowing through them while they lay over a bed of coals. I then measured the exiting air temperature with a digital kitchen thermometer. I found that with about 80 cm of tube length the exiting temperature was around 300 degrees Celsius, which is close to the measured temperature of the coals. It was a crude approach, but it gave me the information I needed.

In between the hot and cold exchangers is a regenerator. A regenerator increases the efficiency of a Stirling Engine. It is not necessary to have one for the engine to run but it does reduce the energy input requirement from the heater and the energy removal requirement of the cooler, making the engine run more efficiently. The way the regenerator works is by storing some of the heat energy of the working gas as it moves from the hot exchanger to the cold exchanger, thereby reducing the cooling requirement of the cold source. And on the return path, as the working gas moves from the cold exchanger to the hot exchanger, it “gains” back that heat energy, thereby reducing the heating requirement of the hot source. The Wikipedia link explains the regenerator in detail http://en.wikipedia.org/wiki/Stirling_engine. The literature I found indicates that stacked wire mesh screens, stacked metal fins, or a bed of spherical balls, serve as effective regenerator material. I personally used steel wool, as recommended by numerous online sources. Figure 9-11 shows a picture of the regenerator. I inserted steel wool into a 2 inch length of copper tube, clipped the ends, and put compression fittings on the ends which allowed it to be attached to the hot and cold exchangers (Figure 12). Unlike some of the other calculations I did, I wasn’t rigorous about choosing the 2 inch length. It just seemed like a good length to use. Besides, I wasn’t sure how to model steel wool in my calculations.

Figure 9

Figure 10

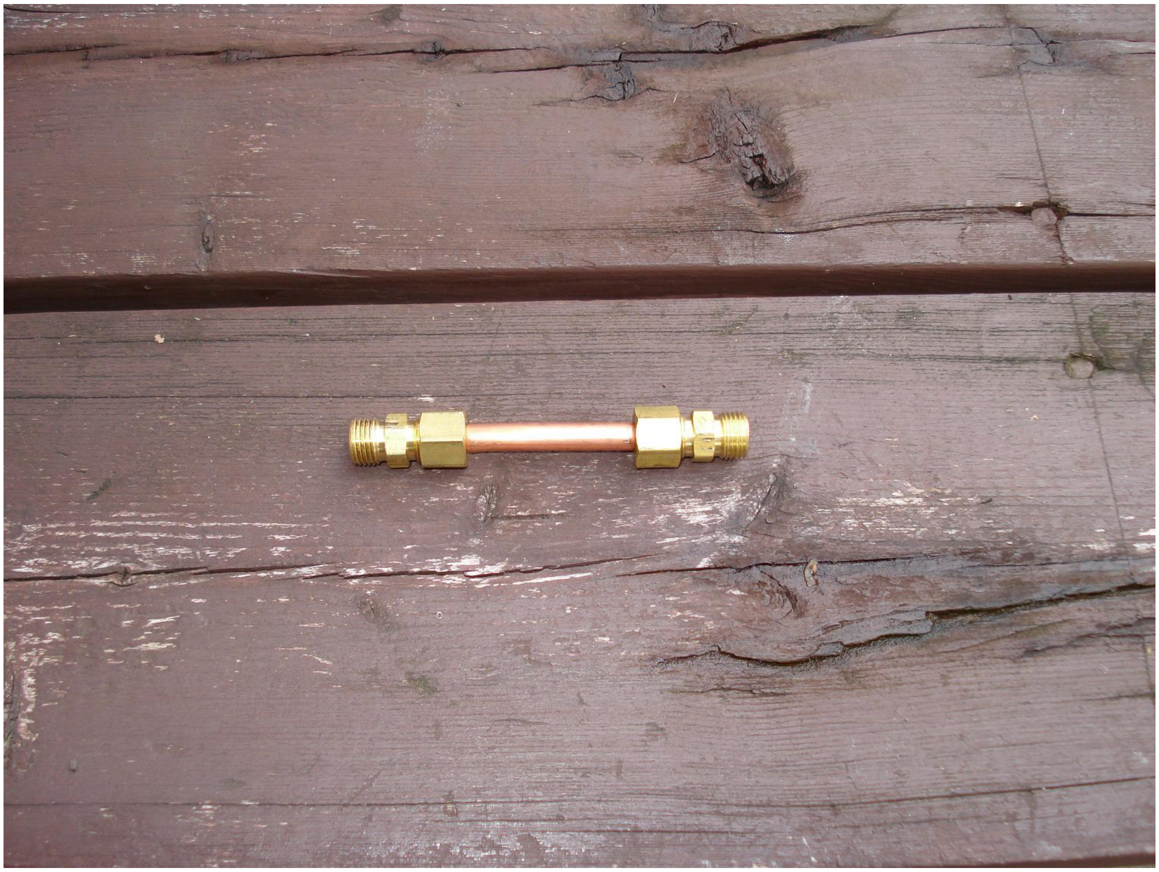

Figure 11

Figure 12

The base, as shown in Figure 6 and 7, was made by first drilling holes into two lengths of 2×6, sized to provide a snug fit for inserting the copper tube. I then flared the ends of the copper tube with needle nose pliers to prevent them from “pushing out” due to the engine pressure. I then drilled a larger shallow hole (not all the way through) around the tube holes which provided a means to make a good airtight seal using the RTV silicone. On the cold side a tireless air valve (Figure 13) was inserted into another drilled hole and secured in place with washers and screws (Figure 14). On the hot side a heat resistant paint (Figure 15) was applied to the wood which increases its resistance to high temperature (Figure 16 and 17).

Figure 13

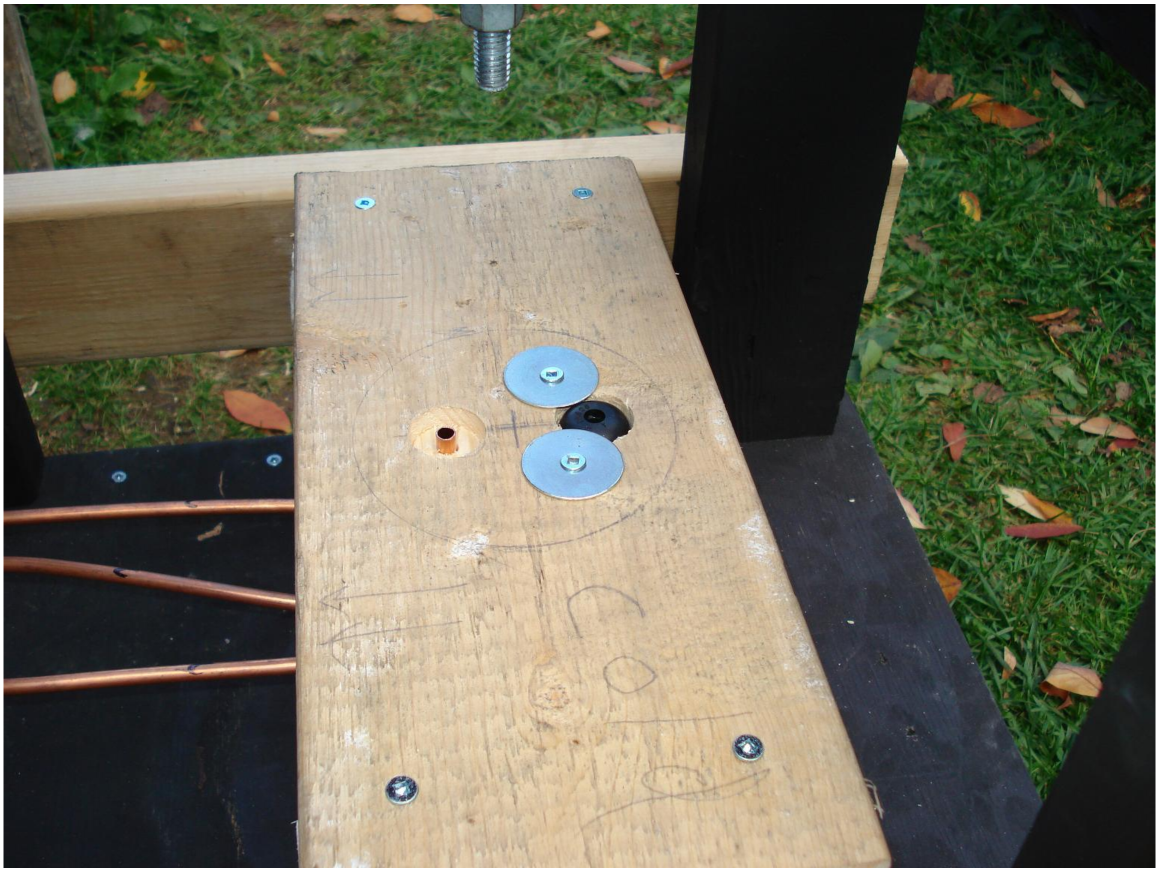

Figure 14


FLAT / MAT
TREMCLAD
BRAND
HIGH HEAT ENAMEL
ÉMAIL HAUTE CHALEUR
650°C (1200°F) • FOR SPECIAL HEAT RESISTANT USES
BBQ's • Fireplaces • Wood Stoves
650 °C (1200 °F) • RÉSISTE À DES TEMPÉRATURES EXTRÊMEMENT ÉLEVÉES
B.B.Q. • Foyers • Poêles à bois
BLACK / NOIR
237 mL
DANGER
FLAMMABLE, POISON / INFLAMMABLE, POISON

Figure 15

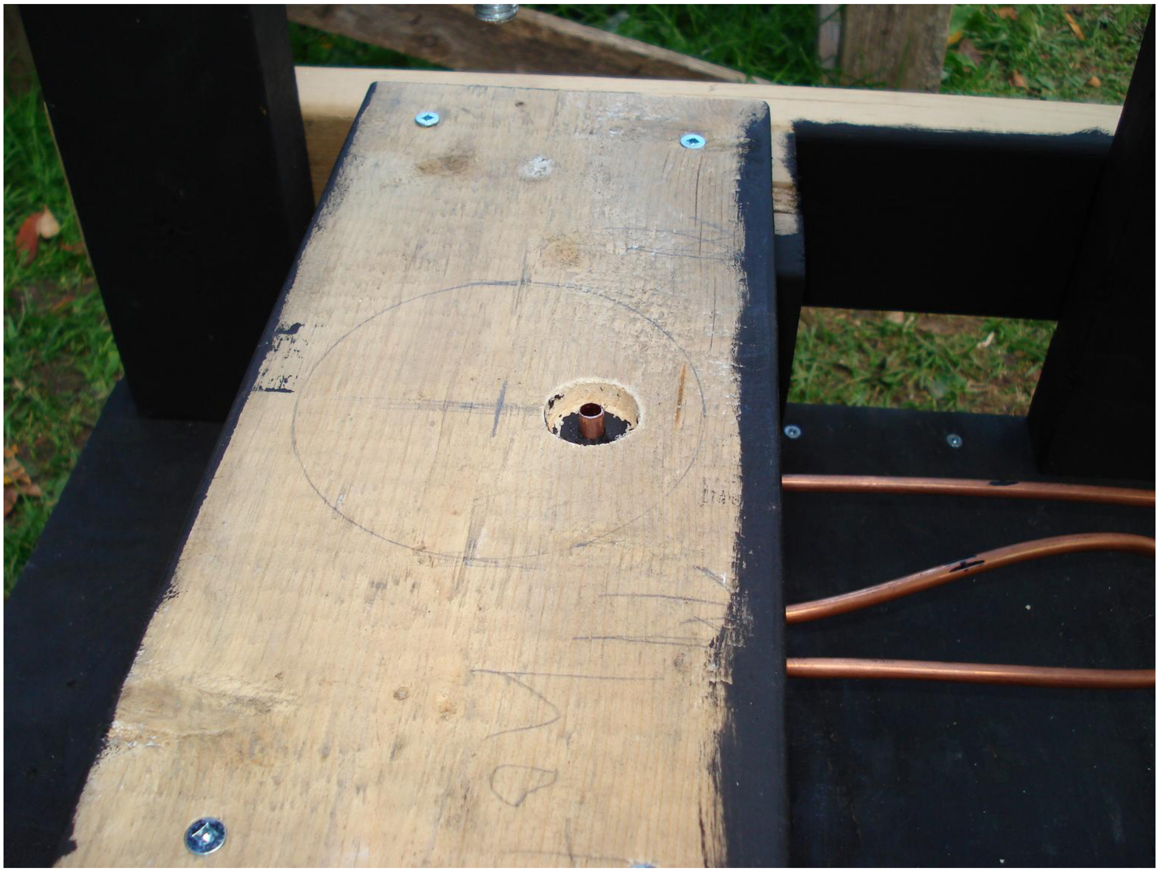

Figure 16

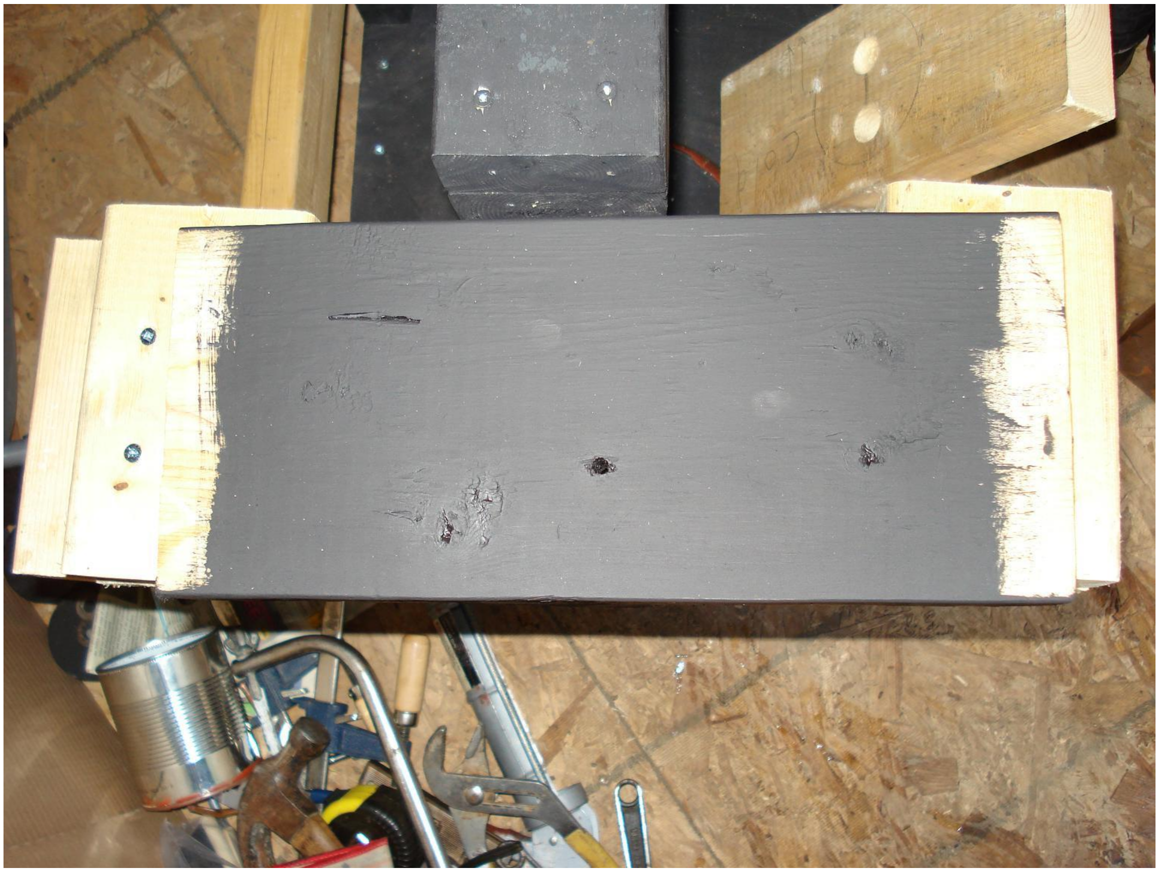

Figure 17: Bottom side

Finally two silicone baking mats were cut to size and placed on top of the two pieces of 2×6, aligned with the holes, with beads of RTV silicone applied underneath for adhesion to the wood. The gaps around the holes were carefully sealed using RTV silicone and then the baking mat surfaces were coated with the RTV. This was especially important for the hot side. The result is shown in Figure 6 and 7.

The two diaphragms were then centered and placed on the hot and cold side bases and carefully sealed around the bottom with the RTV silicone (Figure 18).

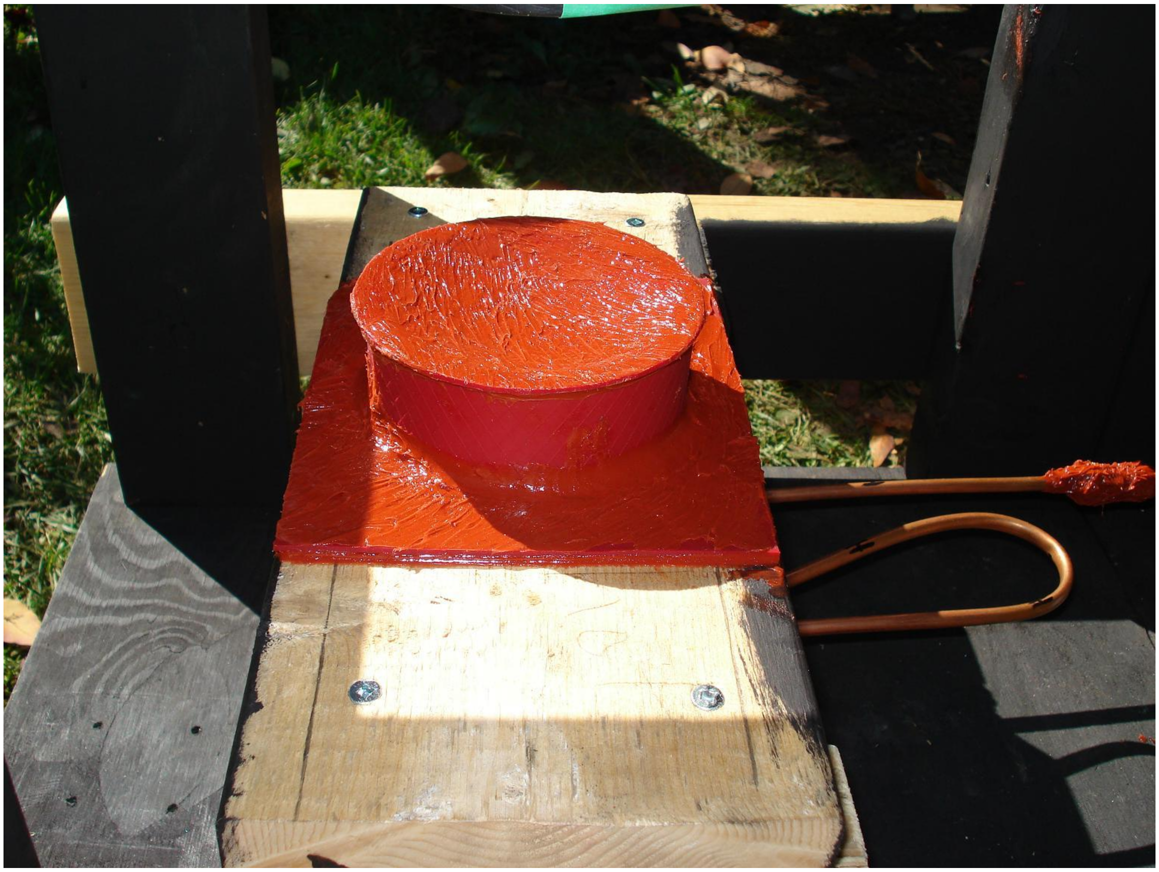

Figure 18

The regenerator was then coated with a copious amount of RTV silicone (Figure 19) to provide thermal insulation on the exterior, which reduces the heat lost to the environment as the hot air passes through. This improves the engine efficiency. There’s also a chance the thick layer of silicone eliminated any small air leak at the compression seal junctions. But most likely the compression seal is already airtight anyway.

Figure 19

Figure 20 shows a picture of the piston over top of the diaphragm. The stroke length of the pistons is 1.5 inches, and at the lowest position of the piston the inside top surface of the diaphragm leaves a 1/8 inch gap with the bottom. This was done to eliminate as much dead (unswept) volume as possible. Unswept volume is the volume in the engine that remains constant as the engine is running. Swept volume is the volume that is "swept" by the motion of the pistons. So if the stroke length of a piston is L, and the area is A, then the swept volume is AxL.

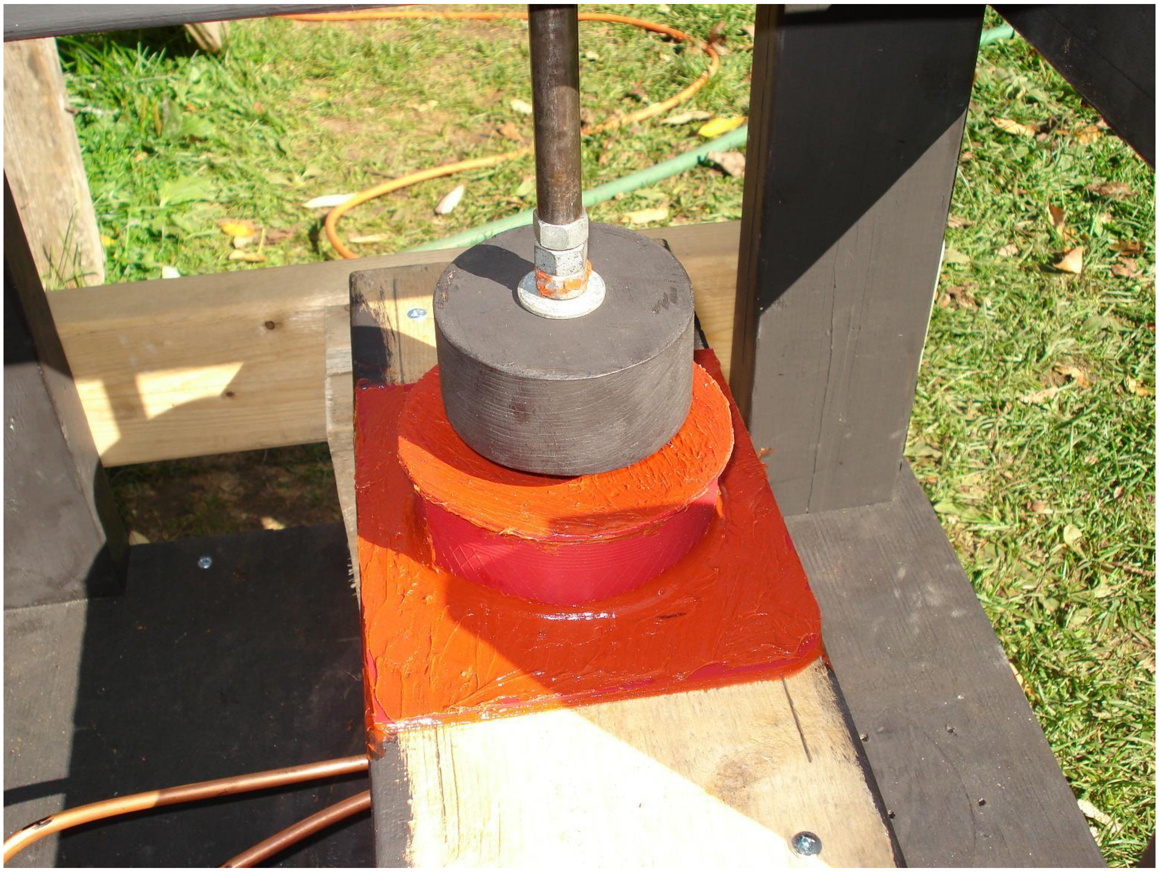

Figure 20

Dead volume tends to reduce engine power, so it must be minimized, especially in the expansion space and compression space (the volumes enclosed inside the diaphragms). Dead volume unavoidably exists in Stirling engines so it is best to keep it in the location of the hot and cold exchangers, and regenerator, since in these locations it can be of benefit and not just a detriment (e.g. longer heat exchangers with greater dead volume can boost heat transfer between the hot and cold source and the working gas. And a larger regenerator can boost its thermal storage capacity making the engine more efficient). Indeed, the optimal design of the Stirling Engine often means balancing conflicting variables.

Metal containers (the kind that hold canned goods) were then placed around the diaphragms in order to help the diaphragms resist the lateral pressure forces (Figure 21). The breaking strength of the baking mats is only 4 MPa (they are 1.5 mm thick) and that of the RTV silicone is 1.5 MPa, so it’s a good idea to support the diaphragms somehow. Also, the piston itself helps the diaphragm resist the pressure pushing up, and the smaller the difference in diameter between the metal container and the piston, the less pressure force acts on the diaphragm. In my case, the diameter of the piston is 3 inches and that of the metal container is 4 inches. This gap (0.5 inch all around) is deliberate so that the diaphragm comfortably “rolls in and out” at the sides, much like a roll sock seal used in some Stirling Engine models. I worked out that with this arrangement the diaphragms can resist over 100 psi engine pressure without breaking.

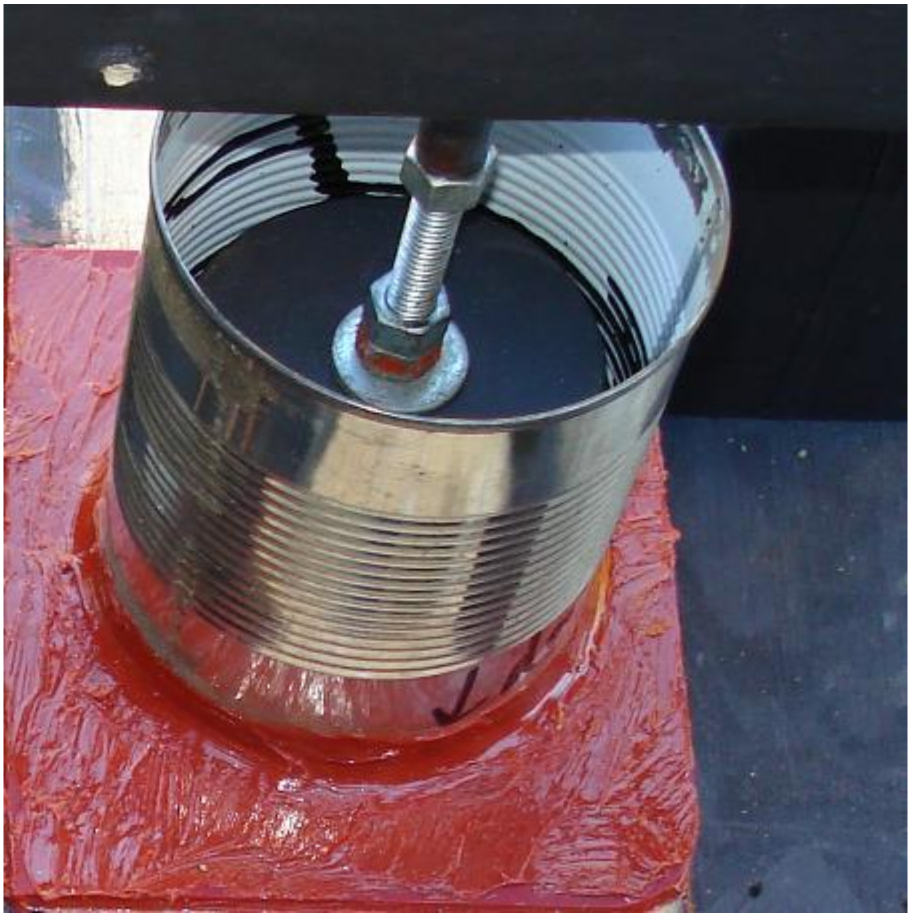

Figure 21: Metal containers placed around the diaphragms and attached to the base with RTV silicone, as it's a good adhesive

A closer look at the final assembled engine is shown in Figure 22-26. Note that the hot side piston motion is identical to the cold side piston motion (sinusoidal). The only difference is that the hot side piston is 90 degrees farther ahead of the cold side piston, in terms of rotational position. For example, when the hot side piston is at the top most position, the engine has to rotate another 90 degrees in order for the cold side piston to reach the same top most position. The Wikipedia link also explains this, for alpha engines: http://en.wikipedia.org/wiki/Stirling_engine.

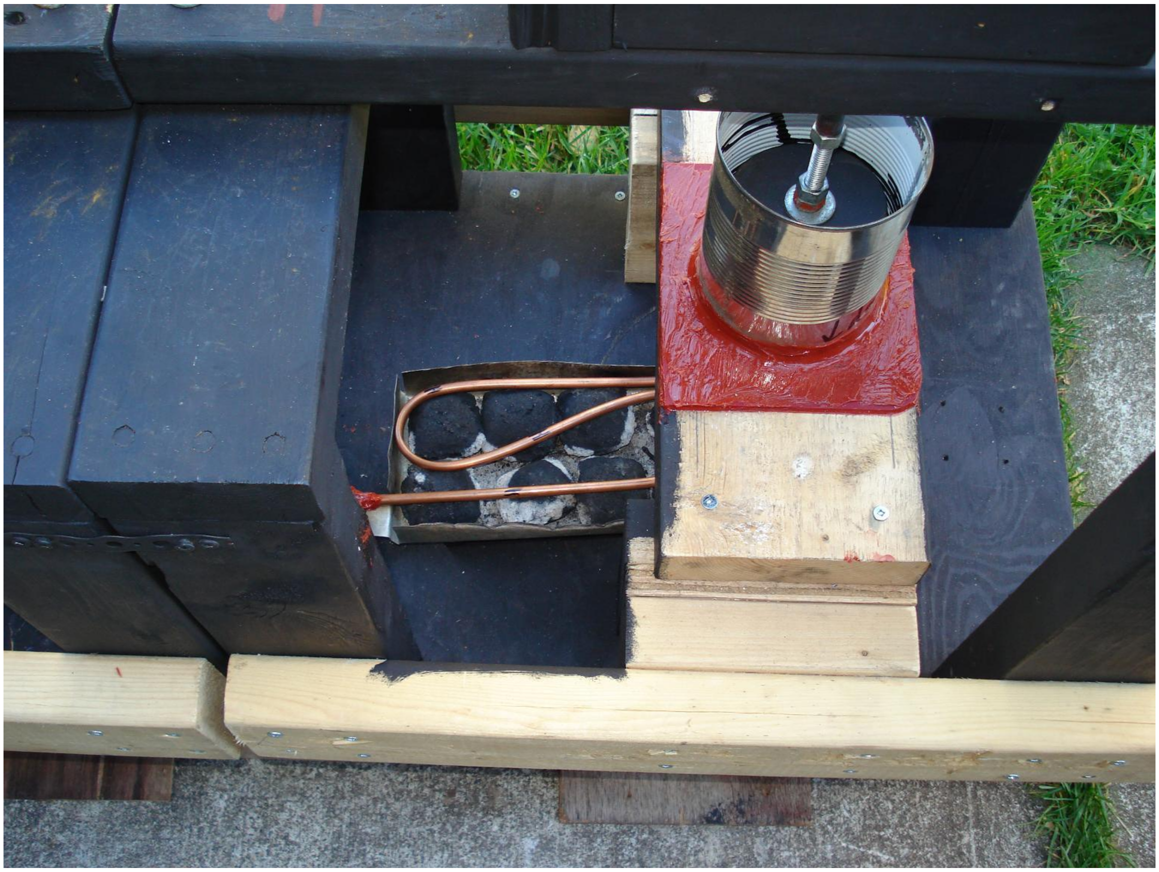

Figure 22: Heater side – using a bed of coals. The measured temperature of the coals was about 300 degrees Celsius, which is close to the temperature limit of the RTV silicone

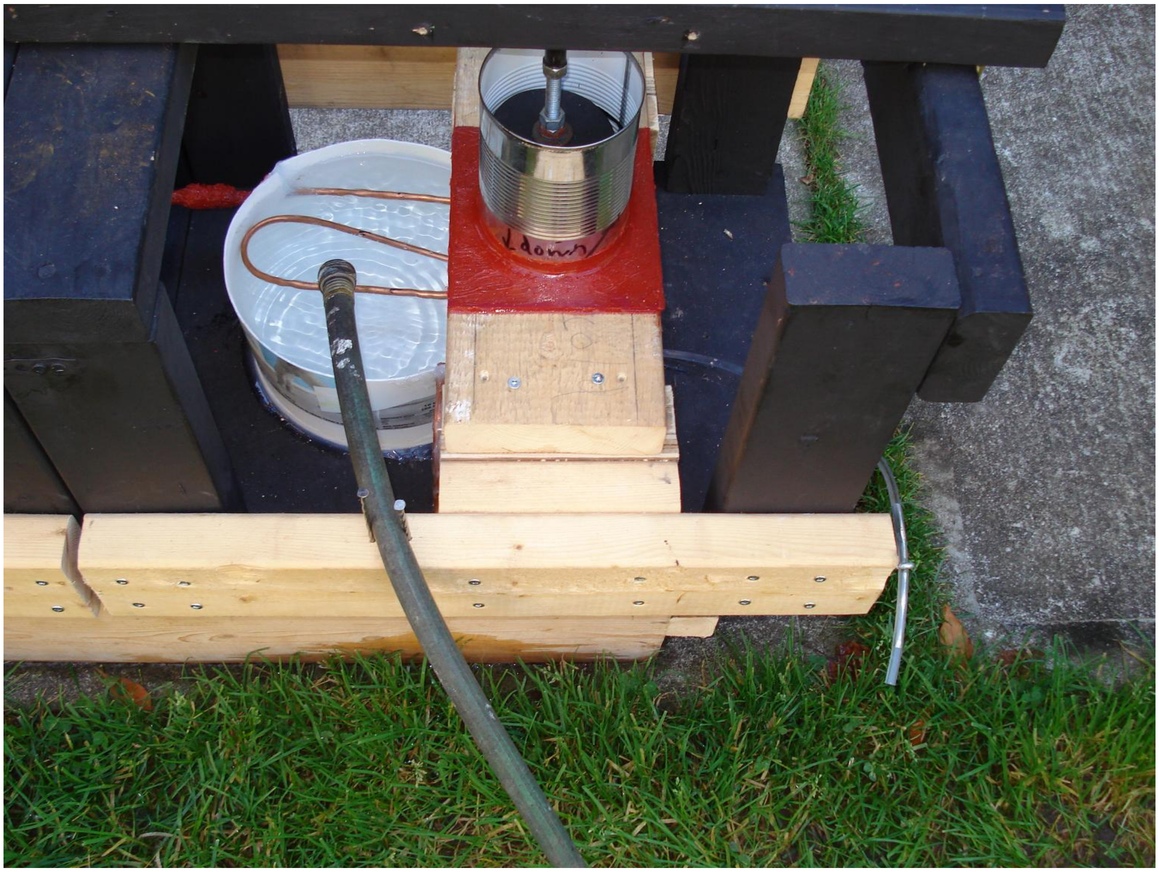

Figure 23: Cooler side – using cold supply water from a garden hose, adjusted to a low flow rate, and collecting in a plastic container. Sealing was done with waterproof GE Silicone II. The temperature of the water was roughly 15-20 degrees Celsius

Figure 24: Water draining from an overflow tube. This keeps the water level constant inside the plastic container

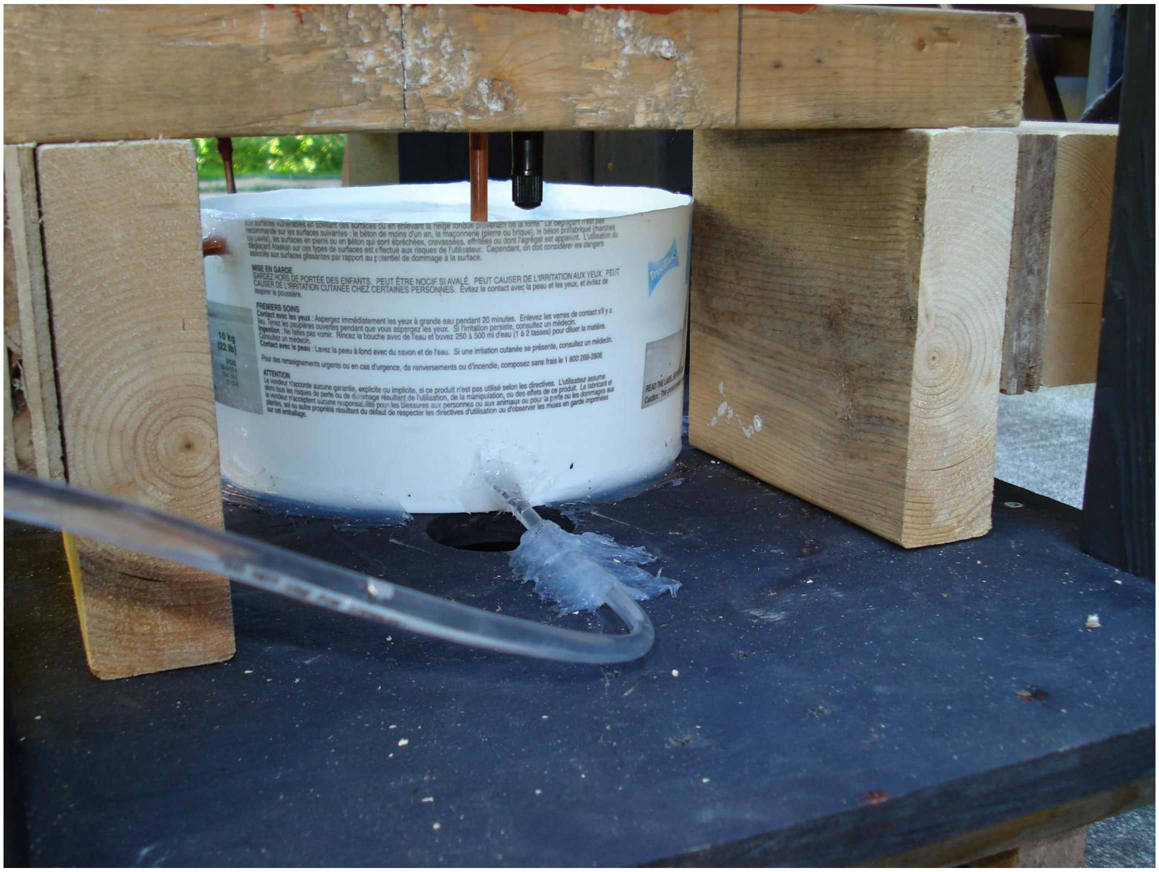

Figure 25: Underside view of the cold side, showing the air valve, and the vinyl tube used to drain the water out of the plastic container when finished. It is manually dropped down so that the water simply drains out

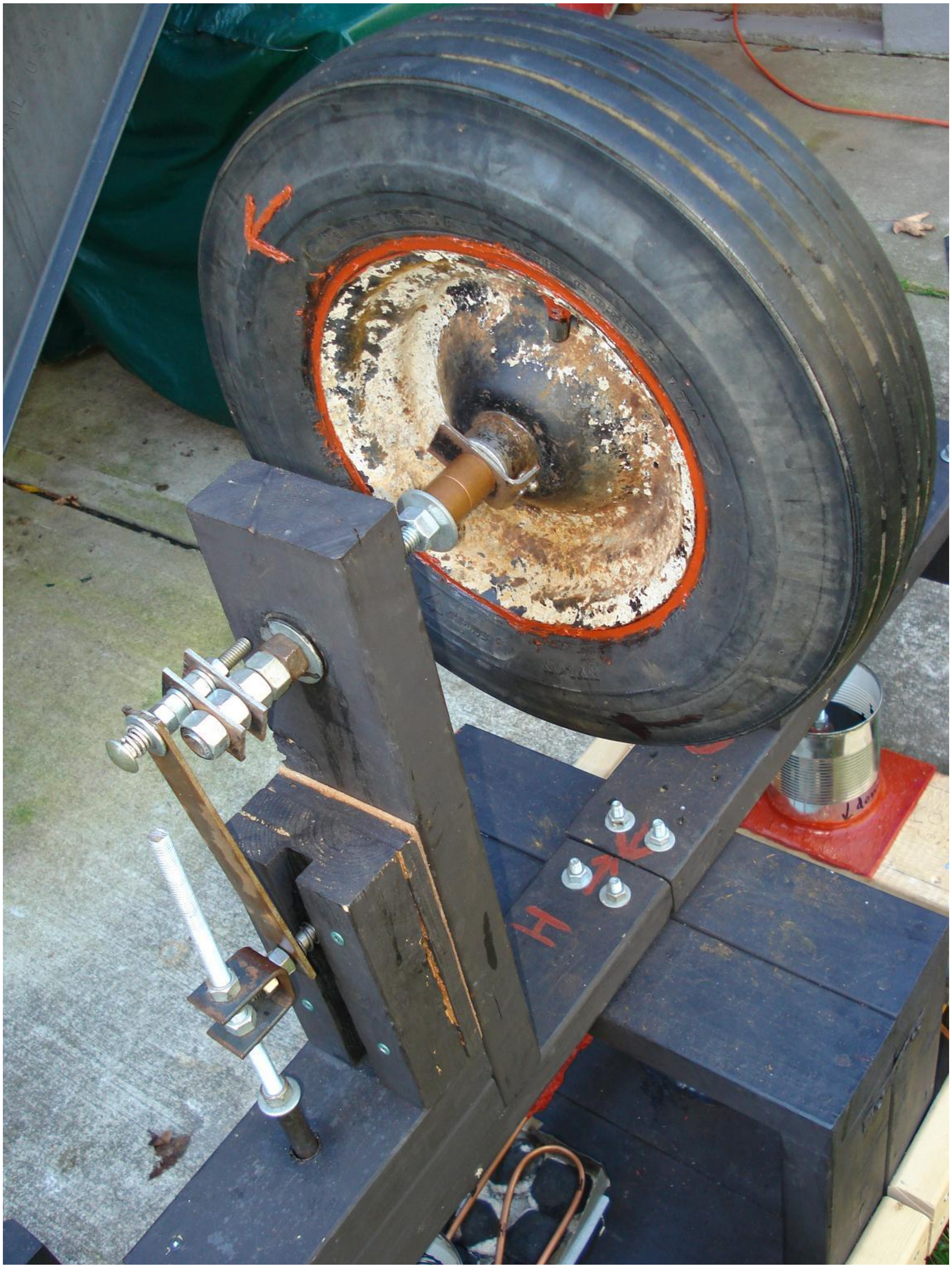

Figure 26: View of linkages and flywheel (taken from an old wheelbarrow). The main parts consist of threaded rods and steel strips cut to size, with holes drilled. The connection piece, through which the vertical threaded rod goes, at the bottom of

the picture, was taken from an old workout bench I no longer use. There was no welding. Only bolts were used to fasten.

Now, it’s best to use something “cleaner burning” than coal if you can, like eco-flame warming gel (used for camping) which is derived from sugar cane. Or you can use another carbon-neutral bio-fuel.

To test the engine it was pressurized with a manual air pump (Figure 27) to 0 psig and 3 psig (at maximum engine volume Vmax – the rest position during pressurization). The engine flywheel was then given a quick spin. But after numerous attempts the engine did not start running. The engine did not even appear to be on the “brink” of running. However, the compression was good and the engine showed no signs of leaking air.

Figure 27

Afterwards, I tried running the engine as a Stirling refrigerator. All Stirling engines will produce a hot and cold temperature difference when rotated by an external power source. So if you attached a motor to the flywheel, one end of the engine would increase in temperature and the other end would decrease in temperature. This is basically a heat pump, and is not too different from how an air conditioner works.

What I did was pressurize the engine to around 1 psig (at Vmax) and cranked the flywheel by hand for a few minutes in the same direction as before, at a speed of about 1 rev/sec. And a temperature difference developed. The original hot exchanger got colder and the original cold exchanger got warmer. The temperature difference obtained was around 10 degrees Celsius. The original hot exchanger

reached 16 degrees Celsius and the original cold exchanger reached 26 degrees Celsius. This might seem a bit counter-intuitive, however.

Note that the initial temperature of the heat exchangers was 17 degrees Celsius – same as the ambient air temperature at the time. See Figure 28 and 29.

Figure 28: Temperature of 26 degrees Celsius

Figure 29: Temperature of 16 degrees Celsius

This result is interesting because it clearly shows that you can run such an engine in reverse and operate it as a refrigerator, or a heater, if you wish. Essentially, it draws heat from the expansion space (it gets colder) and pumps it out of the compression space (it gets warmer).

I had the option of attaching a motor to the flywheel which would have resulted in much faster and more uniform spinning. And no doubt this would have increased the temperature difference, but the linkages where not holding up that well so I decided against it.

In summary, the engine did not run as a heat engine. I pressurized the engine (at Vmax) at 0 psig and 3 psig, and it did not start. It did not even show any signs of “almost” starting. There are clearly mechanical losses, in the linkage mechanism with the “jerky” motion, and probably with the flexing and deforming of the diaphragms as well, just to name a few.

It should be mentioned that at start up (1-2 rev/sec) the power of the engine is low, maybe 5-10 W, with the 3 psig initial pressure (according to my Stirling engine simulator). The simulator I created shows that a much higher engine pressure than what I used is necessary to overcome the friction/losses, and obtain a good running speed. But this pressure, which is on the order of 8-10 bar (120-150 psi) would create too much stress on the linkages (over 800 pounds of upward force!). And the diaphragms may not hold up either.

With higher pressure the engine has more “kick” during the expansion stage. This is the stage of the engine which moves from minimum engine (internal) volume to maximum engine volume. It is this “kick” which allows it to push through the compression stage, which is the stage of the engine which moves from maximum engine volume to minimum engine volume. With enough “kick”, it does this with energy to spare, resulting in a net power output. The flywheel is necessary because it receives the energy of the kick, and due to momentum, pushes the engine though the compression stage. If this kick is not strong enough it simply won’t start. And it means that you either have too little net power output or your engine losses are too high. This kick can be increased in two ways: increase internal pressure and/or increase hot side/cold side temperature difference (usually by increasing heater temperature).

In essence, the kick comes from the expansion of the working gas as it heats up when flowing through the heater and into the hot piston space (which in my case is the diaphragm on the hot side).

Summary

Clearly, I was not able to achieve my goal of building a DIY Stirling engine of decent power using common materials. But I was able to demonstrate its capacity as a heat pump, to an extent, which serves as a way to evaluate how well the thermodynamic aspects of the engine function. Hopefully in reading all of this you have acquired a better understanding of Stirling engine design.

This project has paved the way for me to build another Stirling engine sometime in the future. But it will be made out of metal, especially the linkage and flywheel assembly where smooth mechanical action, and strength is required. The diaphragm/RTV silicone idea may still be used though, but unfortunately it may not have very long life due to the constant “flexing” involved. And also it will not be able to resist very high pressures, and temperatures much greater than 300 degrees Celsius. And high heater temperature is essential for higher efficiency and power. So a metal piston/bore configuration is probably the best solution, especially in the case of high heater temperatures and internal pressure. Good seals would obviously be needed though, such as PTFE – polytetrafluoroethylene (Teflon). But since they cannot resist excess temperature then perhaps a *beta* engine configuration would have to be used instead of an *alpha* configuration. And it may be that an air compressor would have to be connected to such an engine in order to maintain and control the engine pressure, with the compressor output regulated to increase or decrease the engine power (increase or decrease the engine speed, respectively). To increase the engine power, extra air would be pumped in, and to decrease the engine power, air would be pumped out. Ideally any air leak would be small which would minimize the steady-state compressor power required to maintain engine pressure.

Also, it’s better to use a hot side heat exchanger made of stainless steel. The copper tube I used showed clear signs of oxidation which may be fine for temperatures of 300 degrees Celsius, but it won’t hold up for very high temperatures in excess of that (on the order of 700-800 degrees Celsius). Stainless steel is much more resistant to the effects of oxidation at high temperature.

One other point to make is that the regenerator was not that essential for my engine and wouldn’t have made much difference to the outcome. This is because the heating and cooling power of my set up were quite a bit in excess of what I needed to power the engine. Getting high thermal efficiency was not a priority at this stage in my design because I was only interested in having lots of heating and cooling power to get it running. And once it gets running, you can then confidently make the heater and cooler more efficient and focus on minimizing the energy required for each – for example, putting an insulated enclosure around the heat source to help “trap” the heat so that it only gets absorbed by the heat exchanger and doesn’t bleed away to the surrounding air. Once you do this, that’s when a regenerator becomes very important. It helps keep the minimum energy input low.

Here are some more good Stirling Engine links:

Stirling Engine Design Manual, William R. Martini, University of Washington, April 1978. Link:

http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19780016056_1978016056.pdf

Stirling Engine Design Manual, Second Edition, William R. Martini, Martini Engineering, January 1983. Link:

http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19830022057_1983022057.pdf

Dish Stirling Systems. Link:

http://www.nrel.gov/csp/troughnet/wkshp_power_2007.html#dish

This one was key to me being able to create my Stirling engine simulator:

Non-linear Analysis of Stirling Engine Thermodynamics, Oak Ridge National Laboratory, R. D. Banduric and N. C. J. Chen, June 1984. Link:
http://www.ornl.gov/sci/ees/etsd/btric/eere_research_reports/thermally_activated_technologies/engine_driven/stirling_rankine/modeling_and_simulation/ornl_con_154/ornl_con_154.pdf

This next one gives you a good overview of Stirling Engine terminology:

Efficiency Terms for Stirling Engine Systems, Oak Ridge National Laboratory, J. L. Crowley, June 1983. Link:

http://www.ornl.gov/info/reports/1983/3445605890836.pdf

Check this one out. This man built a 2.5 hp gamma Stirling out of his workshop. He calls it "The Jim Dandy # 6″. Link:

http://www.starspin.com/stirlings/jimd6.html

Lastly, here is a list of points I put together which you may find helpful in Stirling Engine design:

• The optimal compression ratio (maximum engine volume/minimum engine volume) that results in the greatest power, is less than 2. Note that the engine volume is the "whole" of the volume contained inside the engine, which includes the volume in the heater space, the cooler space, the regenerator, and the hot and cold side piston spaces. While the volume in the heater, cooler and regenerator remains constant, the volume in the hot and cold piston spaces change over time. So there is a point at which the engine volume is maximum and minimum, hence the ratio. In my design, the compression ratio was around 1.9.

• Regenerator volume is often large compared to the volume of the heater and cooler. It can be as much as twice the volume of either the heater or cooler. It is required in order to achieve high thermal efficiency. In fact, a 1% improvement in regenerator efficiency can improve the overall thermal efficiency by several percent. The more inefficient the regenerator, the greater the required heat flux from the heater and the greater the required size of the cooler, to reach the same power level.

• There is a paradox involving the effectiveness of the heat exchangers and the regenerator. The more effective they are, the more pumping power it takes to "push" the working gas through them. Effectiveness of heat exchangers can primarily be achieved by narrow flow passages, which "constricts" the flow and raises the convective heat transfer rate between the wall of the flow passages and the working gas. But this also increases the pumping power requirement – this translates into an engine loss. Similarly, the effectiveness of the regenerator can be achieved by using a dense matrix material which readily absorbs and imparts heat from and to the working gas, respectively. But a dense matrix material also requires a higher pumping power to "push" the working gas through it. Nevertheless, despite the extra pumping requirements, a Stirling engine runs more efficiently and with greater power when using narrow flow passages and a dense regenerator matrix. One must be careful, however, in not making the passages too narrow or the matrix material too dense, otherwise the pumping loss will exceed any increase in power. This is where optimization becomes critical.

• To reduce regenerator losses it is necessary to limit the level of axial heat conduction (in the flow direction) *within* the regenerator. Axial heat conduction has the effect of “short-circuiting” the heat from the hot side to the cold side and as a result, reducing the effective temperature difference in the engine. The lower the effective temperature difference, the less efficient the engine. To limit this type of loss one can stack wire mesh screens (the regenerator material) perpendicular to the flow direction, which forces axial heat transfer to occur *between* the screens, thereby slowing it down.

• A good way to start a Stirling Engine is by having lower internal pressure, allowing easier effort to “turn over” the engine past the compression stage. And once it starts running increase the engine pressure to increase speed and power. In some cases you need an electric starter.

• The typical heater and cooler (heat exchangers) are made up of many parallel small diameter tubes (1-5 mm inside dia.) with the (working) gas flowing inside them.

• Very high working gas pressures are used because power density is proportional to average gas pressure. Engine losses increase only slowly with gas pressure. A higher temperature difference between the hot and cold side also increases power density and adds to the efficiency.

• Piston seals cannot be oil lubricated as this will foul the heat exchangers quickly. Filled teflon piston rings are sometimes used. Specially designed mechanical seals or oil backed roll sock seals can be used to almost eliminate leakage. In some low power systems, leakage, sliding friction and mechanical wear have been eliminated by using diaphragms or bellows instead of pistons.

• Hydrogen and helium as the working gas, function much better than any other gas (including air) by producing the greatest power and efficiency. Hydrogen is best because it has the highest thermal conductivity, the lowest density and viscosity (resulting in lower pumping losses through the narrow passages of heat exchangers and regenerator), and a low heat capacity on a volume basis. So only a relatively small amount of heat is needed to change its temperature. However, hydrogen permeates through metals and no container is completely impermeable to it. And hydrogen is flammable. Some metals are embrittled by hydrogen. Helium, however, is inert and can be permanently contained in metal. It has an even lower volumetric heat capacity than hydrogen but the viscosity is twice that of hydrogen.

• To predict the rotational speed of a Stirling engine at zero load you have to determine the engine losses due to mechanical losses in the linkages, such as friction, and thermodynamic losses *inside* the engine, such as pumping and hysteresis losses. The rotational speed of the engine dictates the flow rate/losses of the working gas as it flows through the engine. The engine will accelerate until “equilibrium” is reached (constant rotational speed). This is the point at which the raw engine power is balanced by the losses. In other words, the following equality applies in the case of constant engine speed: **mechanical and thermodynamic losses = raw engine power**. In the case where you have a load applied to the engine (such as with a generator) the engine will reach a speed *lower* than the zero-load speed. This corresponds to the same basic equality, but with an extra term added: **mechanical and thermodynamic losses + generator load = raw engine power**. As mentioned, the engine speed at which this equality holds is the *final* rotational speed of the engine. Note that the variables on the left side, including the generator load, are likely *all* a function of the engine speed, making this a non linear relationship, mathematically speaking. Ideally, you want this equality to correspond to the point of maximum generator power output, because that means you get more bang for your buck.