# Design and Analysis of Stirling Engines

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## Abstract

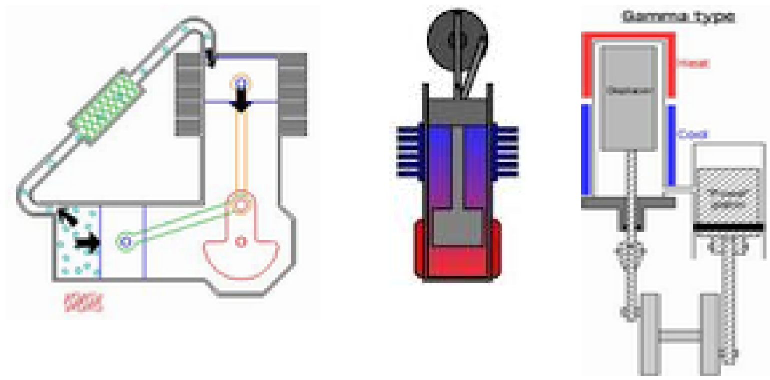
The Stirling engines being researched here are the acoustic engines and the Alpha-V engine. The acoustic engine was built and the Alpha-V was designed. The idea in the beginning was to improve each engine based around efficiency. Theoretically the different designs could be improved based on different factors. The regenerator becomes a big factor in both engines around the thermal efficiency loss. A successful regenerator limits the amount of thermal energy loss while controlling its dead volume. Any form of regeneration limits the loss of heat therefore optimizing any engine performance.

## Introduction:

Heat engines use differences in temperatures to produce some form of functional power. The Stirling engine is no different than these engines. Stirling engines run off of simple heat differentials and use some working gas to produce a form of functional power. The working gas undergoes a process called the Stirling Cycle which was founded by a Scottish man named Robert Stirling. The Stirling Cycle uses isothermal expansion/compression with isochoric cooling/heating. The isochoric means the volume stays the same during the cooling and heating and the isothermal means the temperature stays the same during the expansion and compression. The Stirling cycle has been found to be highly efficient compared to other heat engine cycles even with home built model engines. My goal is to achieve a certain efficiency from one of these model engines built off of my own designs and own materials. Companies mass produce some kits that home machinists build from but my goal was to see if I could get usable power from creating from a design not taken from a kit.

**<u>Research:</u>**

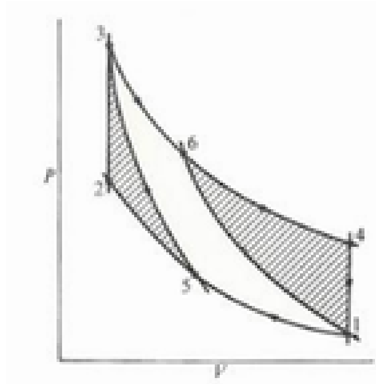
There are three basic types of Stirling heat engines. The Alpha engine is a two cylinder engine with two different pistons. This engine design has been used in a lot of experiments including Solar Power experiments for "green" energy. It has a higher efficiency than the other two types of engines so it is typically used more often. The Beta engine has a one cylinder two piston setup. One piston displaces the working gas and that is called the displacer piston. The other piston runs like a normal piston causing most of the torque on the flywheel and this is called the power piston. The last basic type is called the Gamma engine. This engine is almost identical to the Beta style but uses two separate cylinders for each piston. There are plenty of other variations on these basic types but most of the Stirling engine designs all derive from one of these three basic types.




(From left to right Alpha, Beta, Gamma)

There are many different ways companies utilize these engines today. Most of them are used purely for research but NASA is using them in satellites that they plan to launch in the next few years. NASA will use a free piston design and use radioisotopes to fuel the engines itself. They use this Stirling Convertor for its high efficiency and its low amount of moving mechanical parts. This allows for it to run a little longer than some of the other engines they have. The reverse Stirling cycle is being used as a cryogenic cooler for getting down to cryogenic temperatures. Both the forward and backward Stirling cycles are more efficient than most of the other heat engine/heat pump cycles.

Efficiency of engines is rated around the power they output based off of the energy put into the engine. The Carnot efficiency is the ideal efficiency of any heat engine. This cycle has a theoretical work output equal to the input of the energy. This requires the temperature of the cold reservoir to be at absolute zero which is impossible, the ideal Carnot efficiency therefore becomes purely theoretical.




1-2-3-4 PV Process for Stirling/1-5-3-6 Process for Carnot

Process 1-2 shows the isothermal compression of the Stirling engine. Process 3-4 shows an isothermal expansion. Process 4-1 is the isochoric cooling and 2-3 is the isochoric heating. As for the Carnot cycle 1-5 is an isothermal compression, 5-3 is the adiabatic compression, 3-6 is the isothermal expansion, and 6-1 is adiabatic expansion. The Carnot process allows the environment to create the perfect cycle.

$\xi = -W / Q_h = 1 - (T_l / T_h)$ Carnot Efficiency

$W = -nRln(V_2/V_1)(T_h - T_l)$ Stirling Engine Work

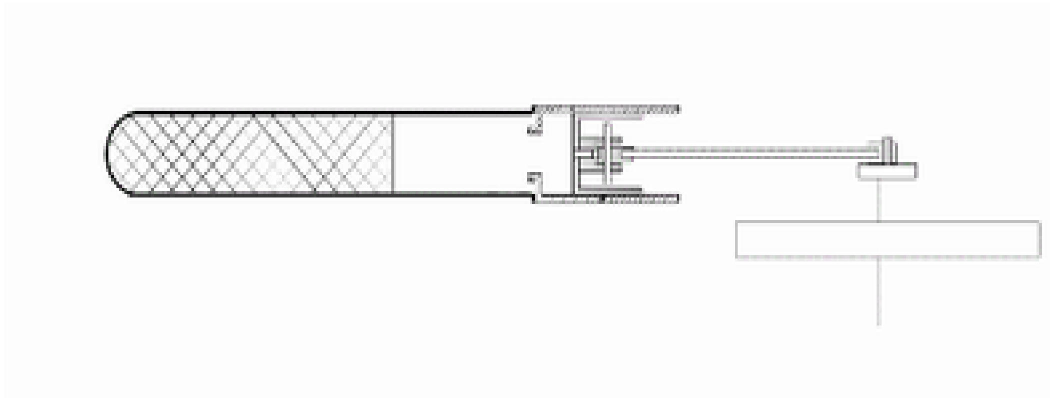
The ideal Stirling efficiency is equal to the ideal Carnot efficiency (proven in math section) allowing the Stirling cycle to have the highest hypothetical efficiencies. No internal energy is lost in the ideal efficiency of the engine because it has a perfect regenerator. The Stirling engine work equation shows that the overall efficiency can be effected by changing the temperature differences, compression ratios, or working gases. Changing all these variables changes the work output from the engine causing its efficiency to increase or decrease. Of course the real work is also affected by the mechanical loss in the engine design itself. This includes parts like the regenerator.

The regenerator also helps the engine achieve its realistic maximum efficiency. The regenerator limits the amount of thermal energy lost throughout the process done by the working gas. When the gas passes through the regenerator while its hot the regenerator stays hot. So then when the gas cools down it has to pass through the heated regenerator again thus preheating the gas when it gets to the warm side. This is the opposite for the cold side but the same idea. This helps make the engine utilize the energy put in by the heat source more than it would without the regenerator creating more work coming from the engine itself.

## Design and Build:

My design phase began by finding a design or designs that were possible to build with minimal parts or designs that could be easily built in a short amount of time. After this was the actual design phase of each engine that was decided on. After the design phase was the build phase where an engine would be built based off of the design. This engine would then be run and improved based on run results. The improvements would then be tested until it could not be made any better.

Two designs were decided upon. The first design chosen was a modified Beta design called an acoustic design. One of the modifications is that it does not use a displacer piston. This engine performs from the pressure variations caused by the changes in temperatures. The pressure changes are modeled by the ideal gas law(PV=nRT). As the temperature goes up at constant volume the pressure also increases. When the temperature hits its highest mark the piston expands the volume of the working gas. Once the volume is expanded all the way the temperature drops at that constant volume causing the pressure to decrease. Once the temperature drops all the way the volume is compressed and the cycle restarts as long as the heat source is still there.



Acoustic Design

The second engine to be designed was an engine based off of the Alpha style. This engine is highly efficient compared to most home built engines as long as it stays airtight. This is a challenge for most because air likes to escape through any minute crack because pressure differences. This engine runs from the same heat source as the acoustic it just uses a different design to get power from the heat differences.

The original design for the acoustic engine was not as efficient as it could be. The working parts had a higher frictional coefficient than a possible design. The initial parts were a metal on metal cylinder piston combination. The improved design uses a pyrex to graphite cylinder. The pyrex graphite combination minimizes the mechanical work loss caused by friction so it increases the work output by the engine. The working gas was designed to be in a pyrex test tube with the heat source at one end and the cold side at the other. Pyrex is a good material to hold heat and not allow it to travel down the material. This is key in increasing the thermal efficiency by keeping the heat from the heat source to travel down the test tube contaminating the cold “reservoir”.

The regenerator for this engine is steel wool. It can hold heat pretty well so when the hot air passes through it stays warm waiting for it to pass through again. This is good for doing the work that a regenerator is supposed to do. The steel wool was chosen for both engines based on its performance qualities for holding a constant temperature. Although the ideal regenerator uses a criss cross pattern specifically it will be very difficult to insure this happens with the steel wool regenerator.

The acoustic engine parts were connected by placing all the parts on a wooden base with mounting brackets for each piece. The flywheel was connected to the drive-shaft of the piston by a thin carbon rod. The flywheel could also be adjusted to control the compression ratio of the working fluid and stroke of the piston itself. The piston and cylinder were connected by a metal sheet and some O-rings. The O-rings were also helpful in creating an airtight seal for the test tube/cylinder connection.

The Alpha-V style engine was designed around any basic V engine design. It has two piston-cylinder sets at a 90 degree offset connected to the same flywheel. My theoretical build for this engine had brass components for the piston-cylinder since they both had low frictional interactions and were pretty light. The connection between the hot and cold air chambers was going to be a thin rubber hose with the regenerator in the middle of this path.

The acoustic engine was built based on the designs. This engine never got running from many different problems addressed in the problems section. The engine was built in a span of a few months. The alpha design never got built because the acoustic engine never got running. Most of the time planned for building the alpha engine got put towards fixing the problems of the acoustic engine.

The ideal efficiency of either Stirling engine is .837 using 1800 Kelvins for the temperature of a candle flame and 293 Kelvins as room temperature. Using a propane torch an ideal efficiency is around .87 using a temperature of 2200 Kelvins for the torch. My goal for the acoustic engine was to get to at least a quarter of the ideal efficiency for either scenario. The total efficiency is limited by the problems caused in the machined parts. For example, Pyrex softens around 1100K only allowing for an efficiency .73 compared to the .837 ideal. Brass softens around 1300K only allowing for an efficiency of .78. These kinds of limitations added to the problems home built engines would have compared to the ideal Stirling engine creates my low estimation of getting an efficiency around a quarter of the highest efficiency.

**<u>Problems:</u>**

A lot of problems arose trying to get the acoustic flow engine to run based off of the regenerator alone. Finding a good regenerator is pretty expensive and engineering it is very difficult. Simply shoving steel wool into the working fluid will create more opportunities for dead volume to occur which can stop the working gas from working at all. There were most likely a few spaces where dead volume caused a little bit of trouble. The piston also showed an expansion of volume in the working gas but would never compress. This means that there may be a potential leakage in the engine itself. Not having the tools necessary to test for air leaks kind of hindered my ability to fix where each leak may have been.

The highest efficiency for this engine would also need to have Hydrogen or Helium gas as its working gas. With the air leakage from open air there was no doubt in my mind any pressure change would create a leak for these lighter gases. Also Hydrogen is flammable so any leak that comes in contact with the fuel source may ignite and cause a lot of problems. My lack of needed building materials and engineering experience hurt the acoustic engine altogether and caused a few problems.

**Conclusion/Further Research:**

Further research to be done on this project includes actually building and testing the Alpha engine. Further research also includes getting the acoustic engine to actually run and into testing. After both engines get running both would undergo testing and hopefully improvements for both. Since they did not get running the hypothetical power outputs were not able to be tested. Efficiency could not be tested at all because of the engine not running. This also means my .21 efficiency goal was also not achieved. Eventually I would like to build these engines and get an efficiency of around .4 at least.

**Math:**

W=Work; P=Pressure; V=Volume; n=molecules; R=Gas constant; T=Temperature;

Q=Heat energy; S=Entropy;

$$W = -\oint PdV = -[\int_{V_1}^{V_2} PdV + \int_{V_3}^{V_4} PdV]$$

$PV = nRT$ Substitute for P since T is constant.

$T_h$=Hot Temp; $T_l$=Low Temp

$$W = -[\int_{V_1}^{V_2} (nR/V)dV + \int_{V_3}^{V_4} (nRT/V)dV] = -[nR(T_h)ln(V_2/V_1) + nR(T_l)ln(V_4/V_3)]$$

$V_4$=$V_1$ and $V_3$=$V_2$ so the work simplifies to $W = -nRln(V_2/V_1)(T_h - T_l)$

$$Q = \int_{S_1}^{S_2} TdS$$

Using the first law of Thermodynamics this becomes

$$Q_h = \int_{U_1}^{U_2} dU + \int_{V_1}^{V_2} (nRT_h/V)dV = 0 + nRT_h ln(V_2/V_1)$$

dU in this case=0 because there is no energy lost in the internal system based on the ideal regenerator

$$Q_l = -nRT_l ln(V_2/V_1)$$

$$\xi = Efficiency = -W/Q_h = -(-nRln(V_2/V_1)(T_h - T_l))/(nRln(V_2/V_1)T_h) = (T_h - T_l)/T$$

Which is the Carnot efficiency which can also be written as

$\xi = 1 - (T_l / T_h)$

**Research Articles:**

(Although no articles were cited these are the articles that I referred to a lot during my research)


1. **"Advanced Stirling Convertor", http://www.grc.nasa.gov/WWW/TECB/rps_asc.htm**

2. **"Stirling Engine" by Gaivoronsky Alexander Ivanovich, http://www.eolss.net/Sample-Chapters/C08/E3-11-02-04.pdf**

3. **Thermal Physics by Daniel Schroeder; Chapter 4 "Engines and Refrigerators"**

4. **"Stirling Engines-Mechanical Configurations" by Dr. Israel Urieli; http://www.sesusa.org/DrIz/engines/engines.html**

5. **"An Introduction to Stirling Cycle Machines" by David Haywood; http://www.occc.edu/gholland/Thermo/Stirling_Intro.pdf**