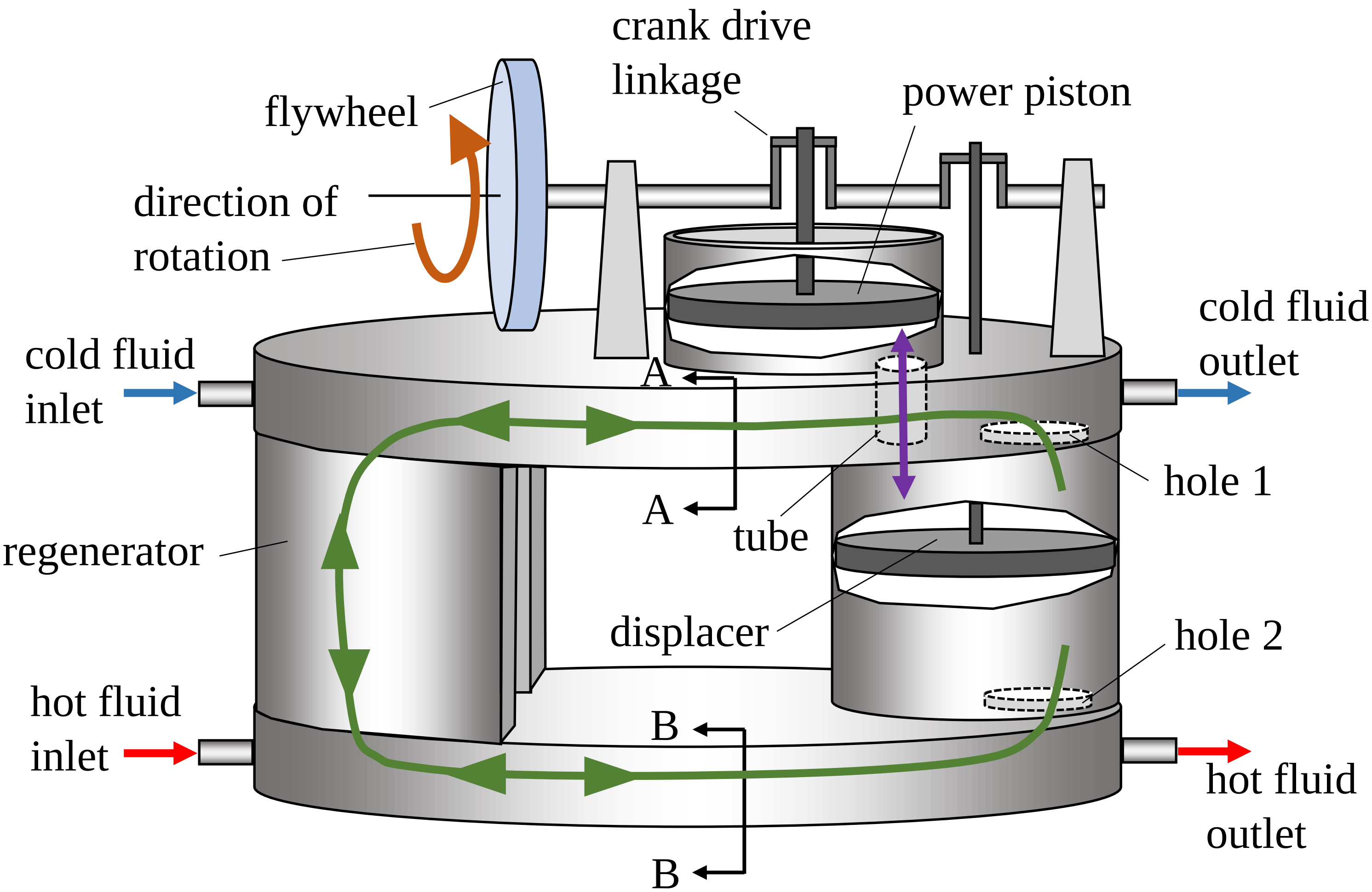
Low Temperature Stirling Engine Design, 2 kW maximum power

Prepared by: Franco Normani

Low temperature Stirling engines are less thermally efficient than high-temperature Stirling engines because of their lower Carnot efficiency. Therefore, they need to be larger in size to produce the same power output. Furthermore, low temperature engines need more heat transfer surface area than high temperature engines. This is because their output power is much more sensitive to the delta-T between the hot/cold source and the working gas. For example, consider a high temperature engine with a hot source temperature of 1000 K and a cold source temperature of 323 K. Now suppose the effective working gas temperature is 950 K and 373 K, at the hot and cold end, respectively. This results in a change in Carnot efficiency from 68% to 61%. Next, consider a low temperature engine with a hot source temperature of 600 K and a cold source temperature of 323 K. Now suppose the effective working gas temperature is 550 K and 373 K, at the hot and cold end, respectively. This results in a change in Carnot efficiency from 46% to 32%. For the high temperature engine, the efficiency dropped 7%, and for the low temperature engine, the efficiency dropped 14%. This means that for low temperature engines, it is more critical to keep the working gas temperature in the hot and cold end as close as possible to the hot and cold source temperature, respectively. Therefore, we must keep delta-T as small as possible in low temperature engines, and this is done by making the heat transfer surface area larger.

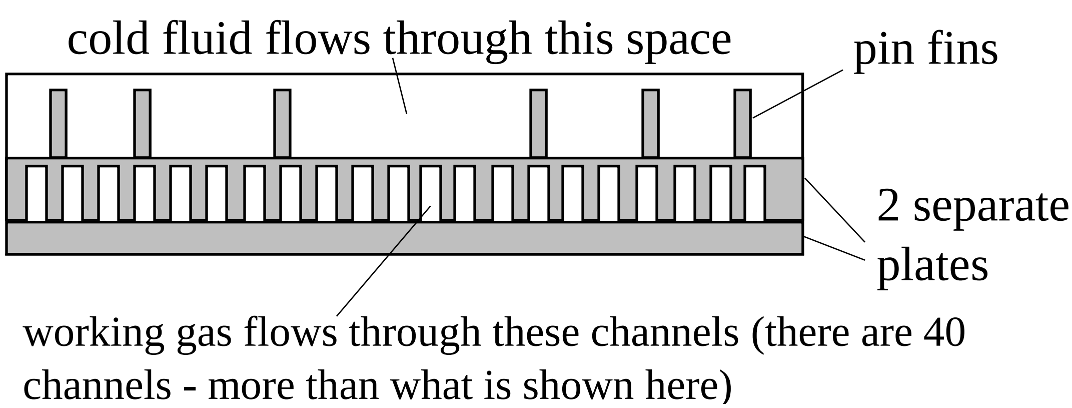
Delta-T must be kept small while also maintaining the level of heat transfer into and out of the engine. Consider the basic equation for rate of heat transfer, which is: Q = (Surface area)×(overall heat transfer coefficient)×(average delta-T between hot/cold source and working gas). From this equation, one can see that, by keeping delta-T smaller, and increasing surface area, the rate of heat transfer can be maintained (i.e. kept constant).

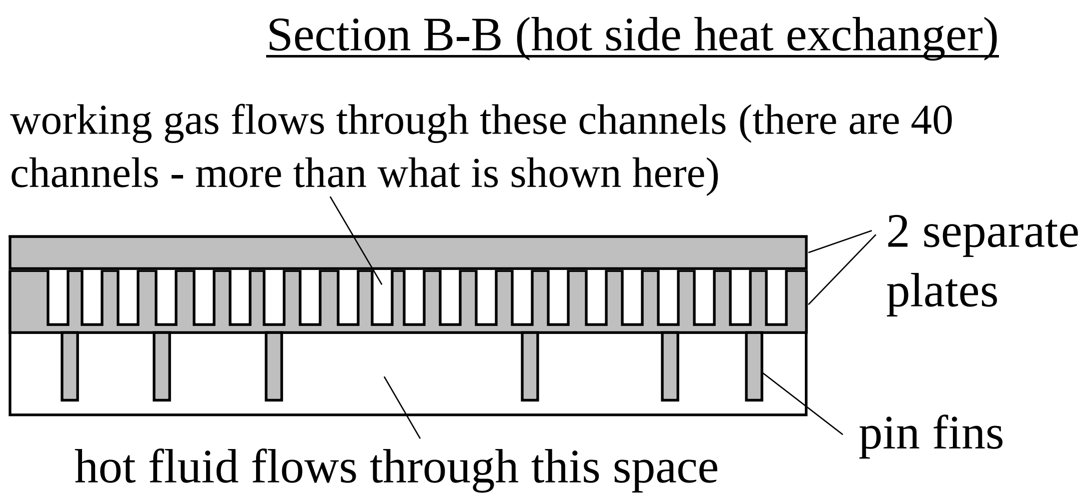
The following is a basic diagram of the proposed low temperature Stirling engine, along with key components labelled.



DRAWINGS NOT TO SCALE

<u>Section A-A (cold side heat exchanger)</u>





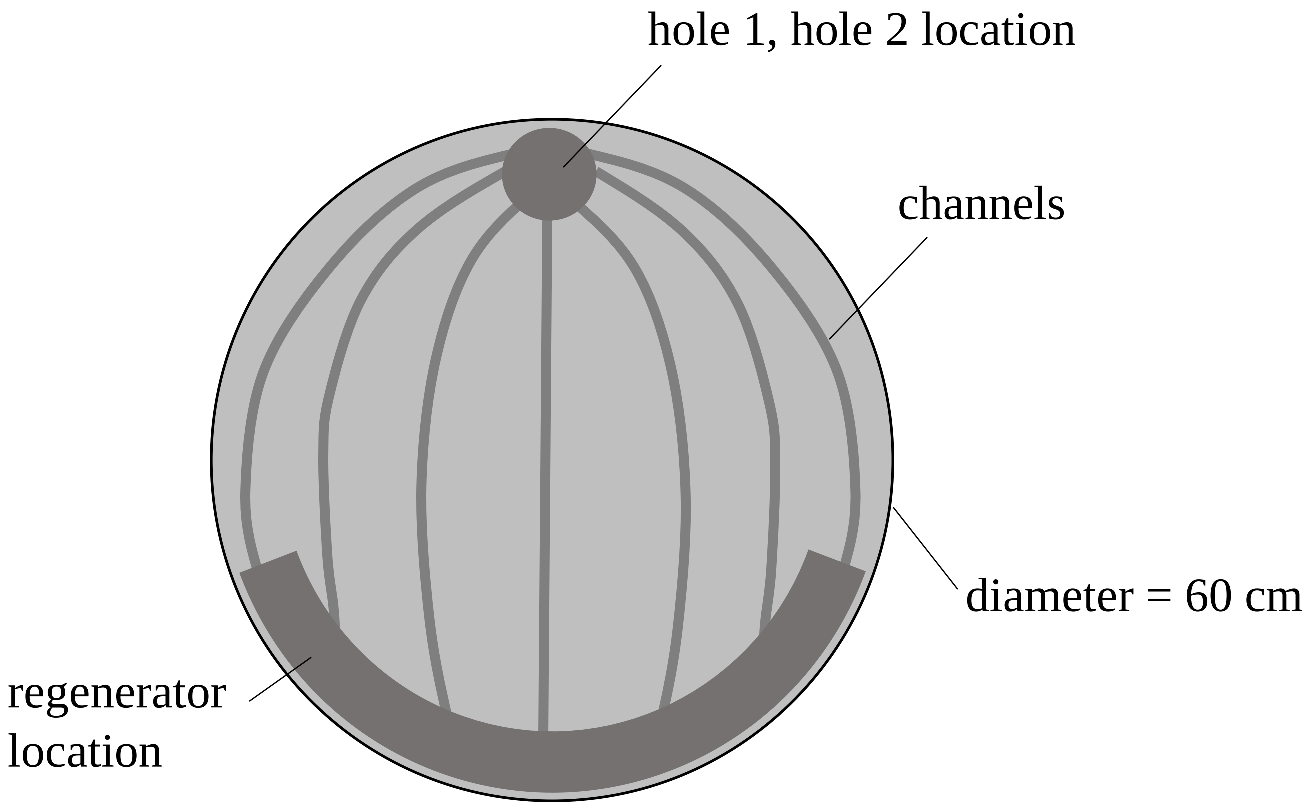
The purple path shown in the first diagram denotes the flow of working gas between the power piston cylinder and the displacer piston cylinder, via the tube shown. The green path denotes the flow of working gas between the compression space and the expansion space (via the heat exchangers and regenerator). Note that there is no mixing of working gas between the two paths. The following are some of the key dimensions to be used for the engine, as seen in the above diagram:

- Diameter of power piston = 18 cm, stroke length = 9 cm
- Diameter of displacer = 20 cm, stroke length = 3 cm
- Void volume of regenerator = 1600 cm^2 (for explanation of this see page 31 of Stirling engine manual)
- The phase angle difference between the two pistons is α = 65 degrees, approximately.

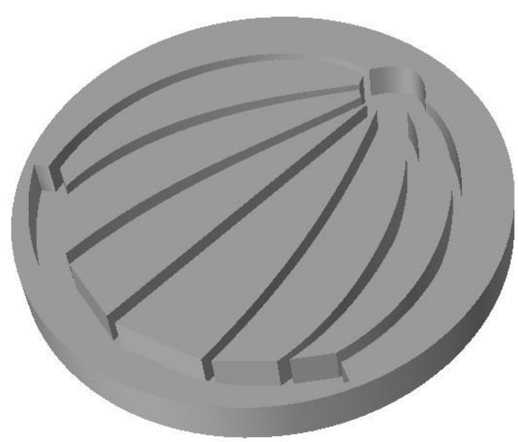
A Closer look at the Heat Exchangers

The following show views of the heat exchanging components of the engine.

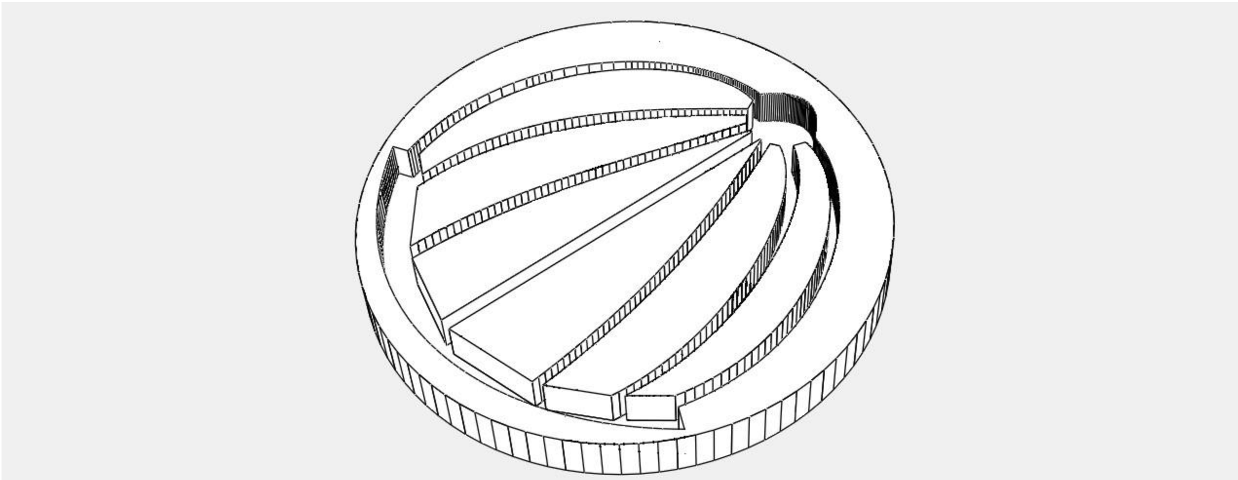
Below is a top view of the hot and cold side heat exchanger.



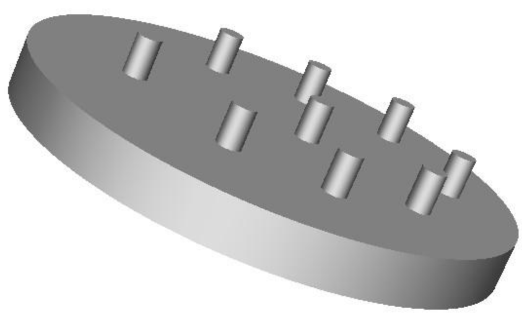
The figure below shows a solid 3D view of the hot and cold side heat exchangers. The channels, hole 1/hole 2 location, and regenerator cavity location are machined into a metal plate. During engine operation, the working gas flows from the hole 1/hole 2 locations, through the channels shown, and then into the regenerator. Note that only a few channels are shown, for clarity. In reality, there are a lot more channels than what is shown. Note that each channel must have the same length/width/depth to maintain uniformity of flow. The optimal number of channels is determined by the Stirling engine software. Use a channel length of 50 cm, a channel width of 0.5 cm, and a channel depth of 0.8 cm (into the thickness of the plate). The optimal number of flow channels is about 40 for the heater and 40 for the cooler.



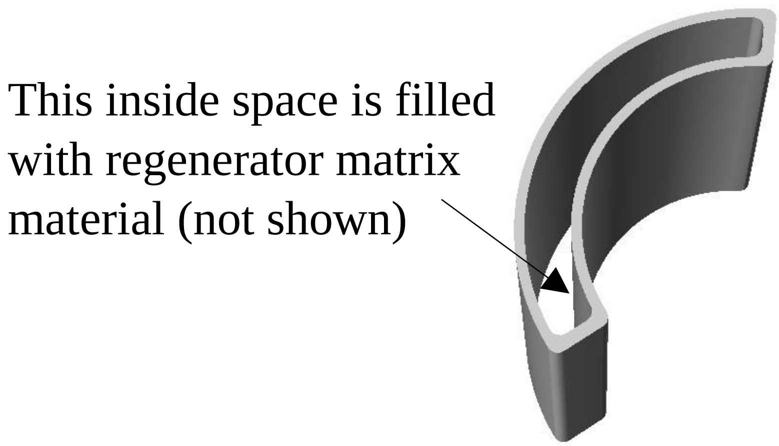
The figure below shows a wireframe 3D view of the hot and cold side heat exchangers.



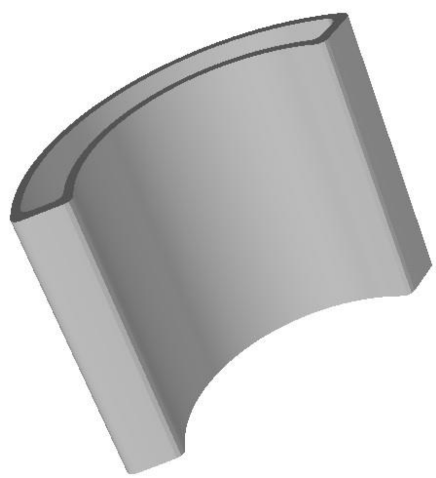
The figure below shows a 3D view of pin fins located on the other side of the hot and cold side heat exchanger (which is opposite the side the channels are on). The pin fins are in direct contact with the hot/cold fluid. The fins are arranged to get maximum rate of heat transfer between the working gas and the hot/cold fluid, keeping in mind that the working gas is oscillating “back and forth” during engine operation, so it doesn’t only flow in one direction. Note that although pin fins are shown, other types of fins can be used, arranged in a manner to maximize the rate of heat transfer between the working gas and the hot/cold fluid.



The figure below shows a picture of the regenerator housing.

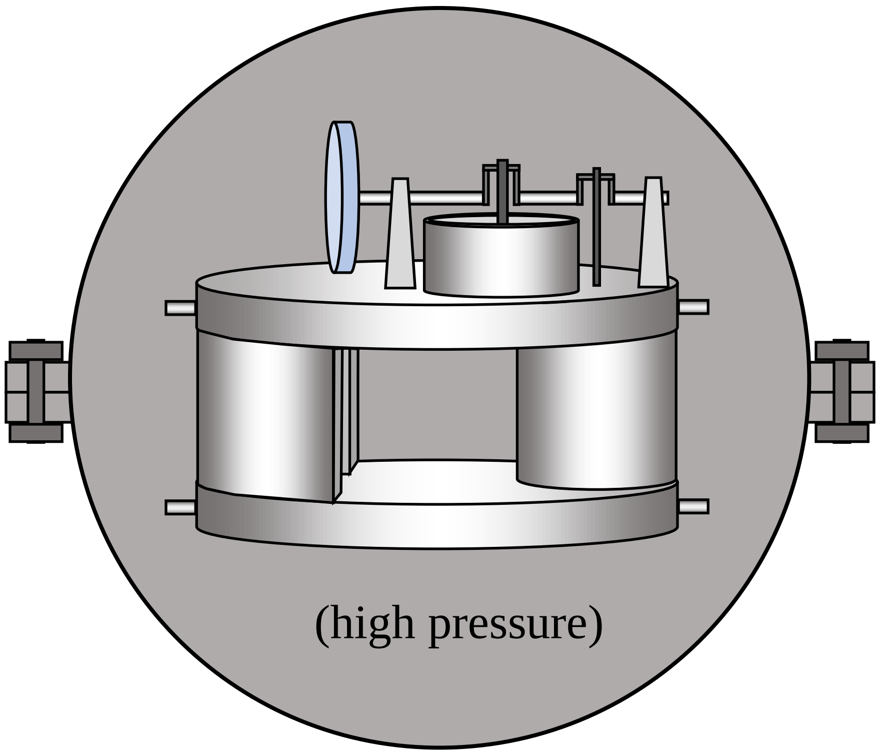


The figure below shows a second picture of the regenerator housing.



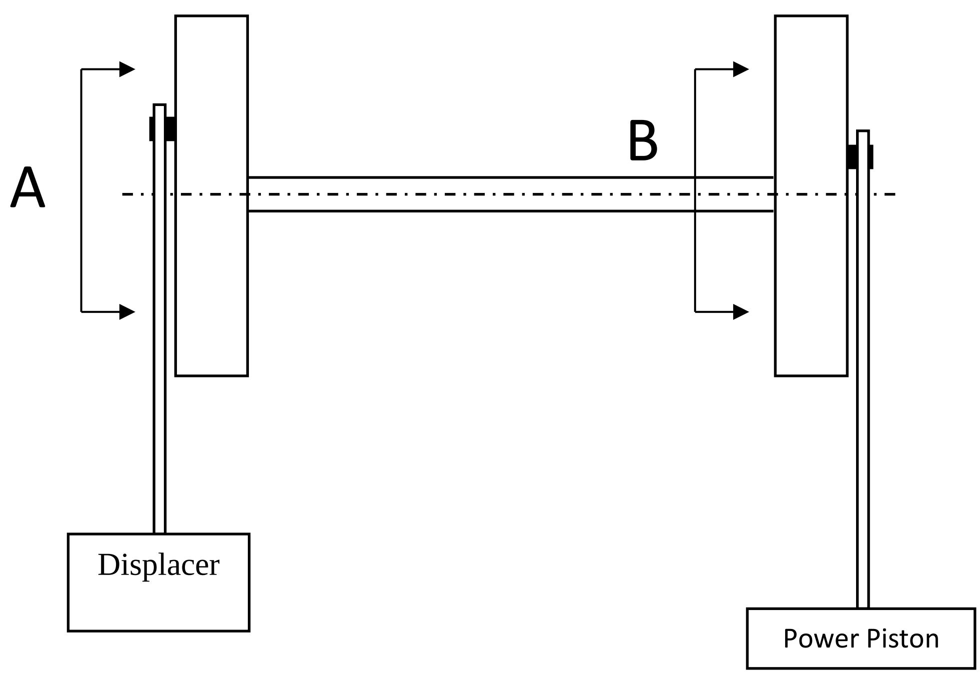
Pressure Vessel for the Engine

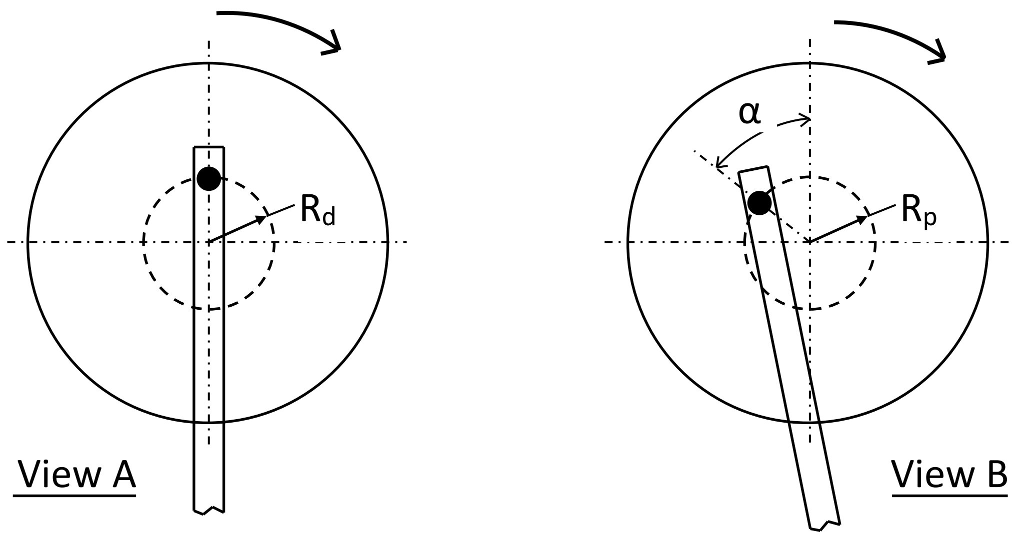
To minimize the stresses acting on the engine frame, the engine must be placed inside a pressure vessel that is pressurized to the mean engine pressure, as shown below. The engine is then connected to an alternator (not shown) to produce electricity. Much of the wiring and tubing that is part of the engine system will have to come out of the pressure vessel (not shown). This allows for external control of the engine without having to open the pressure vessel in order to access the engine.



Crank Drive Design

The figures below show basic a schematic of the crank drive mechanism to be used in this engine, which has a gamma configuration. The phase angle difference between the two pistons is α, and the arrow shows the direction of rotation.





Rotational position of displacer is α ahead of power piston position, as shown in View B

From the figures above, it is evident that the stroke length of the displacer = $2 \times R_d$ and the stroke length of the power piston = $2 \times R_p$. For this engine, use $\alpha = 65$ degrees, approximately.

Performance prediction by the Stirling engine software - with 30 bar average engine pressure (see 'results' file for all the engine parameters used as input)

Engine speed (Hz)	Power produced (Watts)
1	368.213
2	722.479
3	1052.169
4	1347.783
5	1600.458
6	1801.78
7	1943.672
8	2018.358
9	2018.307
10	1936.249
11	1765.151
12	1498.206
13	1128.926
14	650.992
15	58.485

The predicted peak power here is about 2000 Watts and occurs at a speed of 8-9 Hz, which corresponds to a speed of about 500 RPM.

Performance prediction by the Stirling engine software - with 1 bar average engine pressure (this means that the engine is not pressurized)

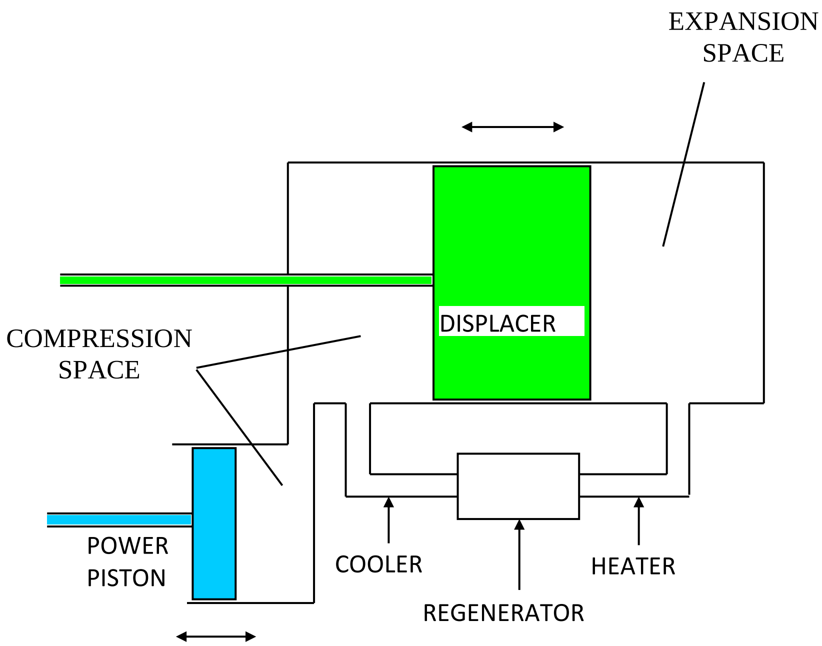
Engine speed (Hz)	Power produced (Watts)
1	12.144
2	23.177
3	32.253
4	38.617
5	41.563
6	40.429
7	34.584
8	23.432
9	6.414

The predicted peak power here is about 40 Watts and occurs at a speed of 5 Hz, which corresponds to a speed of about 300 RPM.

Therefore, for high engine power you need to pressurize the engine.

Gamma Configuration

The figure below shows a basic gamma configuration for a Stirling engine, which is the configuration used for this particular engine design.



Additional information

- This engine design is partly based on the information provided by the following thesis on a 2.5 kW LTD Stirling engine: *Stirling Engine for Solar Thermal Electric Generation*, Mike Miao He, Electrical Engineering and Computer Sciences, University of California at Berkeley, http://www2.eecs.berkeley.edu/Pubs/TechRpts/2018/EECS-2018-15.pdf
- The Stirling engine manual also has to be read in order to gain a more complete understanding of Stirling engine design, and to better understand the content presented here.
- The tube joining the space between the power piston cylinder and displacer cylinder should be about 2-3 inches in diameter to minimize flow losses as the working gas shuttles back and forth between these two spaces. Similarly, hole 1 and hole 2, shown in the first diagram, should also be 2-3 inches in diameter to minimize flow losses.

- Use a hot side temperature of 280 degrees Celsius for optimization and performance predictions. Temperatures lower than this will result in less power. Assume the cold side temperature is 50 degrees Celsius.
- Insulate around the hot end of the engine to reduce thermal losses to the environment.
- Perhaps use a regenerator matrix material made out of fiberglass, but keep it inside a fine mesh so the fibers don't blow around the inside of the engine during operation.
- The ideal porosity of the fiberglass is about 86%, which can be achieved by compressing it to 30% of its original (uncompressed) volume (based on Berkeley thesis description on page 32).
- The two separate plates making up the heat exchanger assembly must be joined together with enough bolts to prevent "separation" when the engine is pressurized. A separation would seriously compromise heat transfer and hurt engine performance.
- Use aluminum components for the engine housing, where possible, and steel for the crankshaft and linkage components for maximum strength.
- The alternator connected to the engine will function as a generator to produce electricity, and as a starter to start the engine.
- At the topmost and bottommost position of the displacer it should almost touch the top and bottom (respectively) of its cylindrical housing. This is to minimize dead volume in the engine.
- At the bottommost position of the power piston it should almost touch the bottom of its cylindrical housing. This is to minimize dead volume in the engine.
- To keep the engine well sealed around junction points, to minimize gas leakage and pressure loss, use high temperature silicone (RTV silicone) which is cheap to buy and can withstand a continuous temperature of 316 degrees Celsius.
- The pressure vessel for the engine must be able to withstand high internal pressure which is to be equal to the mean engine pressure. The engine is pressurized separately from the pressure vessel. Use a mean engine pressure of 30 bar. During operation, the pressure inside the engine will approximately fluctuate between 23 bar and 38 bar.
- The engine must be dynamically balanced.
- The optimal fin arrangement for optimal heat transfer must be determined using suitable software.
- Use Nitrogen as the working gas inside the engine.
- Special attention must be given to the bearing selection used in the moving parts of the engine, such as the linkages that move the power piston and displacer. The power piston and displacer must move up and down with ease with minimal lateral movement and lateral forces.
- Components must be sized appropriately to withstand forces during engine operation. Note that the forces acting on the power piston linkage are large, while the forces acting on the displacer linkage are relatively small.
- The pressure inside the engine is fairly uniform.
- Use filled PTFE (Teflon) seals between the power piston and cylinder wall and between the displacer and cylinder wall, in order to prevent gas leakage.

- The hot and cold fluid need a high flow rate through the heat exchanger to maintain a roughly constant hot/cold temperature at the heat exchanger surface. This improves the thermal efficiency of the engine.
- The optimal heat exchanger is one that maximizes the rate of heat transfer between the hot/cold fluid and the working gas. This needs to be accomplished by maximizing the overall heat transfer coefficient in the heat exchangers, while also minimizing the difference in temperature between the hot/cold fluid and the working gas (which is flowing through the flow channels).
- See 'results' file for engine performance predictions created by the software program.
- Since the engine will be placed in a pressure vessel, then engine lubrication (such as used in the linkages) will be exposed to high pressure. Care must be taken that the lubrication is safe in this high pressure environment.
- Do not use oil-based lubrication in the contact area between the power piston and cylinder wall, nor between the displacer and the cylinder wall. Any lubrication used here must be "dry", such as with PTFE seals. Any oil-based lubrication can evaporate under the high-pressure and high-temperature conditions and foul the heat exchangers, which will then be much less effective.
- Other design issues, not mentioned, will surely arise.

See disclaimer: https://www.real-world-physics-problems.com/disclaimer.html