Modification of a Stirling engine for low ΔT operation

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Bachelor's thesis in Energy Technology
Bergen, Norway 2019

Høgskulen på Vestlandet

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IMM 2019-06

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Norsk tittel:	Modifisering av en Stirling-motor ved lav ΔT-drift
Author(s), student number:	Amparo Tarazona Ferrandis, 582491
Study program:	Energy Technology Engineering
Date:	[June 2019]
Report number:	IMM 2019-05(M82)
Supervisor at HHVL:	Norbert Lümmen
Assigned by:	HVL
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Antall filer levert digitalt:	*none*

Preface

This bachelor thesis was written by Amparo Tarazona Ferrandis at the Department of Mechanical and Marine Engineering at Western Norway University of Applied Sciences (WNUAS), to conclude the study program of Industrial Engineering in Universidad Politécnica de Valencia. The project was assigned and supervised by Professor Norbert Lümmen.

This thesis has the aim of studying the response of a beta-type Stirling engine with high and low temperature heat source. Other students built this engine as part of a previous thesis. It must be made operational again, be tested with high temperature heat source, and then, after changing the crankshaft, be tested with both high and low temperature heat source.

I would like to thank my supervisor Professor Norbert Lümmen for its help and advice during all this process, Arne Høeg for its help solving every problem that the engine presented, and Frode Wessel Jansen and Harald Moen for their help and work in the engine lab with the experimental part of the project.

Abstract

In this project, the analysis of a beta-type Stirling engine is carried out. The engine was constructed by other students of this university as part of their bachelor thesis in 2011, and then started and tested in the current configuration as part of another bachelor thesis in 2013.

Despite it was originally designed and optimised for use with a high-temperature heat source, it can be modified for low ΔT operation by changing the crankshaft for a new one with a reduced stroke.

In the beginning, the plan for the project was to make the engine operational again and test it in its current configuration, in order to compare the results with the results of the previous report. After that it was planned to make the necessary modifications, and test it for low ΔT operation, with the exhaust gases from another engine as the heat source.

It was filled with helium and tested with a propane burner as heat source, and these results were compared with the ones obtained in 2013.

Then the crankshaft was removed, in order to replace it for the new one. However, when it was tried to mount the guiding rings on it, they did not fit. Since there was not time enough to order new ones, the engine could not be tested in low ΔT operation

Sammendrag

I dette prosjektet utføres analysen av en Stirling-motor av beta-typen. Motoren ble konstruert av andre studenter på dette universitetet som en del av bacheloroppgaven i 2011, og startet og testet i den nåværende konfigurasjonen som en del av en annen bacheloroppgave i 2013.

Til tross for at den ble opprinnelig designet og optimalisert for bruk med en høytemperaturvarmekilde, kan den modifiseres for lavt ΔT-drift ved å bytte veivakselen til en ny med redusert slaglengde.

I begynnelsen var planen for prosjektet å gjøre motoren operativ igjen og test den i sin nåværende konfigurasjon for å sammenligne resultatene med resultatene fra forrige rapport. Etter det ble det planlagt å foreta de nødvendige modifikasjonene, og teste den for lavt ΔT-drift, med eksosgassene fra en annen motor som varmekilde. Motoren ble fylt med helium og testet med en propanbrenner som varmekilde, og disse resultatene ble sammenlignet med de som ble oppnådd i 2013.

Deretter ble vevakselet fjernet for å erstatte den for den nye. Men da det ble forsøkt å montere ringene på den, passet de ikke. Siden det ikke var tid nok til å bestille nye, kunne motoren ikke testes i lavt ΔT -drift.

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1. Introduction

Interest in Stirling engines has increased a lot in last years. As it will be explained in further sections, the characteristics it has, such as low pollution and the possibility of using a big range of heat sources, make it very interesting.

The engine analysed in this report is a Beta-type Stirling engine located at the WNUAS, that has not been used for some years.

In 2011, the design, building and setup of a test jig for this engine was carried out by a group of students as part of their bachelor thesis. They also made an investigation of the feasibility of using a Stirling engine to recover waste heat.

Then, the engine was started and tested as part of another bachelor thesis in 2013. The purpose of this was to examine the effect of this engine in relation to expectations of pressure, temperature and Beale factor.

The plan for this project is to make the engine operational again and test it in its current configuration, in order to compare the results with the results of the report from 2013. After that it was planned to change the crankshaft, and test it for low ΔT operation, with the exhaust gases from another engine as the heat source.

1.1 History

The Stirling engine was invented in Scotland by Robert Stirling, who intended to create a safer alternative to the steam engine. The first patent was filed in 1817, where he presented the engine and the “economiser”, the predecessor of the regenerator (see **¡Error! No se encuentra el origen de la referencia.**).

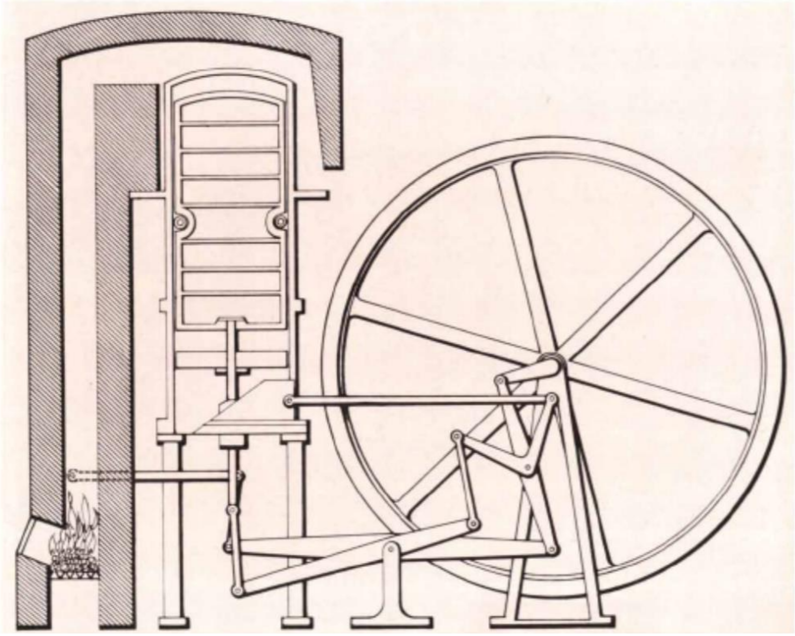

Figure 1. Sketch of the engine presented in the patent [4]

It was used in the beginning of 19th century to pump water, but due to some technical issues and the rapid development of internal combustion engines, it was abandoned for a time.

Two more patents were presented by Robert and his brother, James, in 1827 and 1840, that consisted on improved configurations of the original engine. By 1845 it had sufficiently increased the power output for it to drive all the machinery at a Dundee iron foundry.

During the later 19th hundreds of small Stirling engines were built and used for applications where a small power source was needed. However, they were eventually substituted by the electric motor and small internal combustion engines.

It was after the Second World War when interest in these engines increased again, when technological advances allowed to obtain more power with smaller and cheaper engines.

2. Advantages and disadvantages

As it is explained in this section, despite it still presents some troubles, Stirling engines have some properties that make them very attractive nowadays.

2.1 Advantages

Energy source

Since Stirling engines only need an external heat source to work, a big range of sources can be used, such as solar energy, burners with any kind of fuel, like biomass for example.

High efficiency

The Stirling engine is the only one able to reach efficiencies close to the Carnot efficiency. In fact, it reaches it theoretically.

Environment

Due to its closed working cycle and the possibility of using a continuous combustion process, the emissions are reduced compared to reciprocating internal combustion engines, for example. This makes this engine very respectful with the environment.

Security

Unlike other machines, the Stirling engine uses a single-phase working fluid, keeping internal pressures close to the design pressure and reducing the explosion risks.

Flexibility

It has a lot of applications, such as waste heat recovery, and thanks to its reversible working cycle, refrigeration and heat pump. This will be explained in further section of the report.

Easy maintenance

The Stirling engine is an external combustion engine, which reduces the wear of the internal parts of the engine.

Low temperature response

This kind of engine works better with low ambient temperatures, unlike internal combustion engines, that have problems with cold temperatures.

2.2 Disadvantages

High cost

Stirling engines require heat exchangers which contain the high temperature working fluid and must withstand the corrosive effects of the heat source and the atmosphere. This requires using expensive materials that rise the cost of the engine.

Big size

These engines need a big heat exchange surface, what makes them bigger heavier than a generic internal combustion engine with the same output power.

Slower start

In order to start working, they need to warm up first. This makes them not suitable for applications that require fast starts or rapid changes of speed.

Security

As said before, in some respects it is safer than other engines. However, it can still be dangerous, depending on the working gas used. If the engine uses air as the working fluid, the mixture of air and lubricating combustible fluids inside the engine can produce explosive mixtures due to the oxygen contained in the air, a danger that is accentuated in high-pressure engines [1].

3. Configurations of the Stirling Engine

In this section, the most common configurations of the Stirling engine will be described. There are some levels of classifications for these engines, but generally they are classified by the forms of cylinder coupling: alpha coupling, beta coupling or gamma coupling.

In all configurations here described two pistons are employed, both mechanically linked to an output power shaft. However, depending on the configuration, there will be one or two cylinders, and the function of the pistons will change.

On the illustration in Figure 2, the most common configurations are shown with its most important parts named.

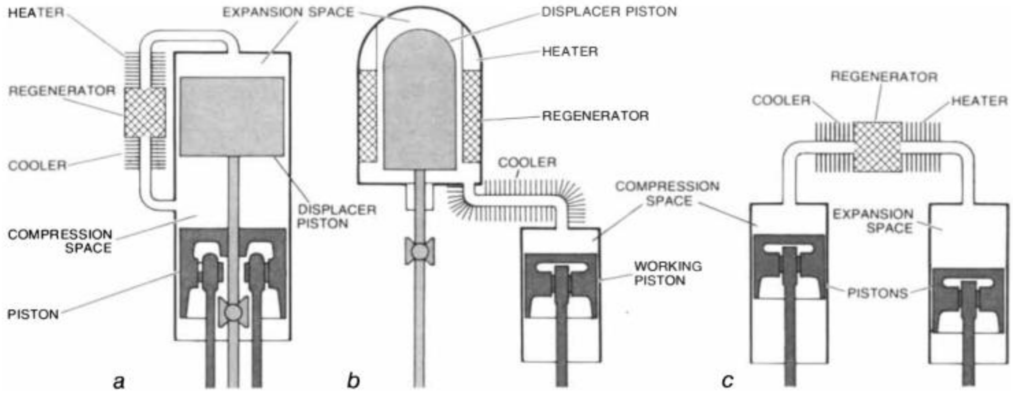

Figure 2. Common configurations of Stirling engines: beta (a), gamma (b) and alpha (c), [4]

3.1 Alpha-type

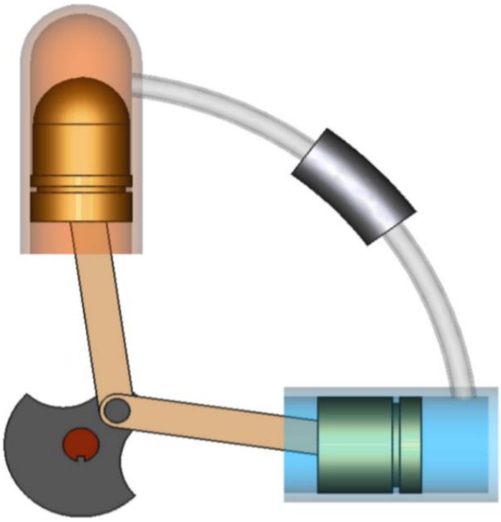

Figure 3. Alpha configuration [6]

This type of engines has the two pistons in two separate cylinders (see Figure 3). One of them is constantly heated by the heat source, the other one is constantly cooled by the refrigeration system, and there is a pipe, where the regenerator is placed, connecting them and allowing the flow of the working gas from one cylinder to the other. Conceptually, it is the simplest configuration, but it has the disadvantage that both pistons need to have seals to contain the working gas.

3.2 Beta-type

Beta engines have one single cylinder, where both pistons are placed. The main function of the lower piston, which is called power piston, is to transfer the expansion work to the crankshaft. On the other hand, it uses work from the crankshaft to compress the working fluid in the engine. The upper piston is called displacer, and its function is to move the gas from the cold end to the hot end of the cylinder. Both are connected to the crankshaft by different linkage to maintain the phase angle.

The heat source is placed in the top of the engine, so that the expansion space is the space in contact with the topside of the displacer, and the cooling system is in the lower end of the cylinder. The compression space is the space between the two pistons.

The problem with configuration is that it cannot have an important regeneration function. By creating an external path for the gas, as indicated in Figure 4, and placing the regenerator there, this problem can be solved.

The engine studied in this report is a beta-type. It will be described with more details in further sections.

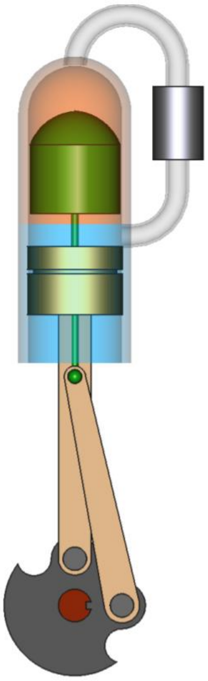

Figure 4. Beta configuration [6]

3.3 Gamma-type

This configuration also has a displacer and a power piston, with the same functions described before. The difference between this type and the beta-type is that they are placed in two different cylinders. This means that the compression space is split between the two cylinders with an interconnecting transfer port, as shown in Figure 5. The heater, the cooler and the regenerator are placed the same way as in beta type.

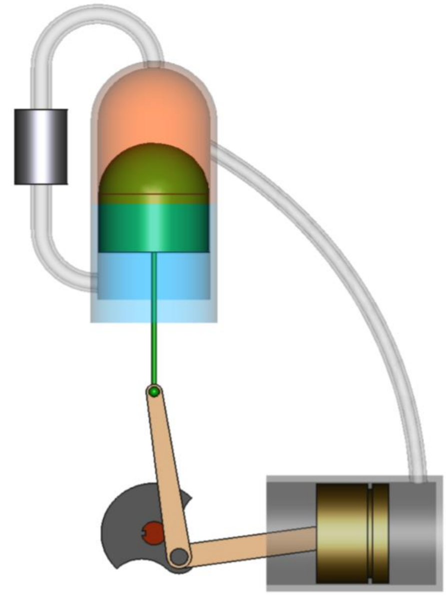

Figure 5. Gamma configuration [6]

4. Stirling cycle

4.1 Ideal Stirling cycle

The ideal Stirling cycle is a closed and thermodynamically reversible cycle that consists of four processes (also shown in Figure 6):

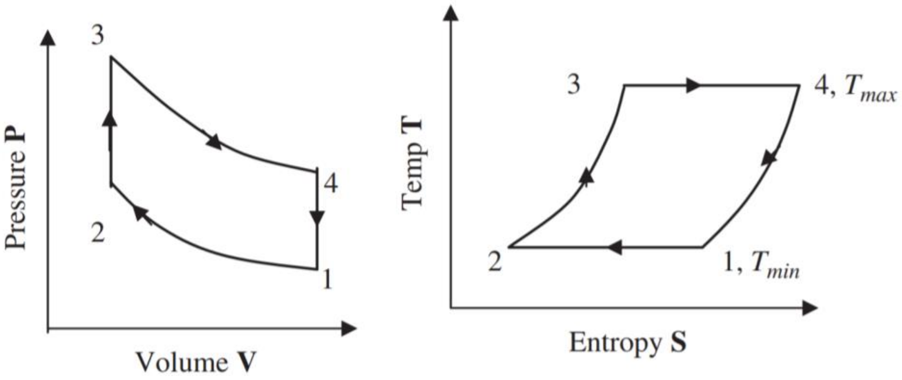

Figure 6. *P-V* and *T-S* diagrams of the ideal Stirling cycle [8]

Process 1-2: Isothermal compression

In this process, the power piston moves towards the displacer, compressing the gas. While the pressure increases, heat transfers from the gas to the cooling system so the temperature remains constant. This heat rejected from the cycle equals in magnitude to the work done on the working gas.

Process 2-3: Isochoric heat transfer

The displacer moves towards the power piston, moving the gas from the cold end to the hot end of the cylinder and while keeping the volume constant. In this process the working gas passes through the regenerator, which transfers heat to the gas, increasing its temperature and its pressure. No work is done in this process.

Process 3-4: Isothermal expansion

The gas starts expanding, moving the displacer and the power piston. The pressure decreases as volume increases, and the heater transfers heat to the working gas, keeping its temperature constant. The heat supplied equals in magnitude to the work done by the working gas.

Process 4-1: Isochoric heat transfer

The displacer moves away from the power piston, moving the gas from the hot end to the cold end of the cylinder and maintaining volume constant. In this process the working gas passes through the regenerator, where heat is transferred from the gas to it, reducing its temperature and its pressure. No work is done in this process.

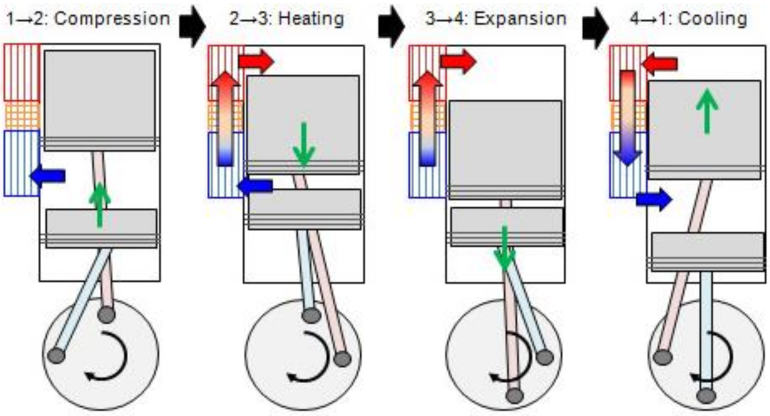

Figure 7. Motion of the pistons and the working gas for these four processes in a β-type Stirling engine.

4.2 Actual Stirling cycle

The assumptions made to obtain the cycle described before are invalid in actual engine operation. Since the input heat exchanger cannot operate ideally, there is a considerable amount of energy wasted on it. The same happens with the regenerator, that will not be able to return all the heat deposited in it during part of the cycle.

Other things to take in account are that the cylinder walls cannot provide a sufficient heat transfer to ensure the isothermal conditions, and that there are frictional losses between the gas and the engine, and between all the parts of the engine that are constantly moving.

All this makes the cycle reduce from 1-2-3-4 to 1’-2’-3’-4’, as shown in the figure.

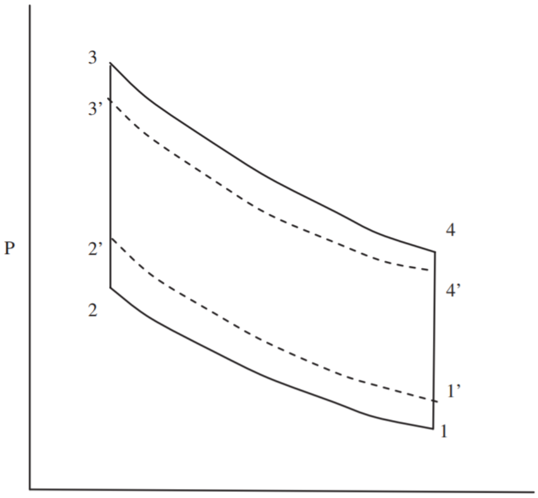

Figure 8. Actual Stirling cycle [8]

5. Applications

As mentioned before, the Stirling engine has several advantages that make it very interesting. With the environmental problems that the world is experiencing nowadays, its high efficiency and low pollution, and the wide range of heat sources that can be used, increase the interest on develop and improve this technology.

5.1 Energy recovery

Generally, thermal machines need high temperature heat addition. However, the Stirling engine only needs a small temperature differential in order to turn received heat into mechanical energy. For this reason, it can make profit of many residual energies that cannot be used in other machines. Despite the lower efficiency they have with respect to the Stirling engines that use other heat sources, they use energy that otherwise would be wasted, and this increases the efficiency of the whole system.

A good example of this heat sources is the exhaust gas from an internal combustion engine. In this kind of engines, a big percentage of the energy contained in the fuel is wasted as heat. Any company that uses internal combustion engines on its production process could use this wasted heat on the exhaust gases to run Stirling engines and obtain electrical energy that can be sold or used by the own company.

Another good example is the heat wasted on the refrigeration of nuclear power plants. In these power plants, the steam leaves the turbines with a big amount of thermal energy and it needs to be condensed. As said before, this heat wasted on the refrigeration can be used to obtain electrical energy by using Stirling engines.

5.2 Refrigerator and heat pump

As said before in this report, the Stirling cycle is reversible, which makes possible to use Stirling cycle machines for applications as refrigerators and heat pumps.

If mechanical work is done on the engine by an external source, and the process curves in the *T-S* and *P-V* diagrams run counter clockwise, the Stirling cycle engine operates as a refrigerator and/or heat pump.

A heat pump and a refrigerator work the same way, both of them transfer heat from a cold space to another warmer by consuming mechanical work. However, the aim of the refrigerator is to extract heat from the cold space and maintain it cold, and the aim of the heat pump is to add heat to the hot space and maintain it warm.

Several sources can be used to provide mechanical work to the shaft of the machine, that will drive the pistons. When the working gas is compressed, this will release heat, working in the practice like a heat pump or a refrigerator.

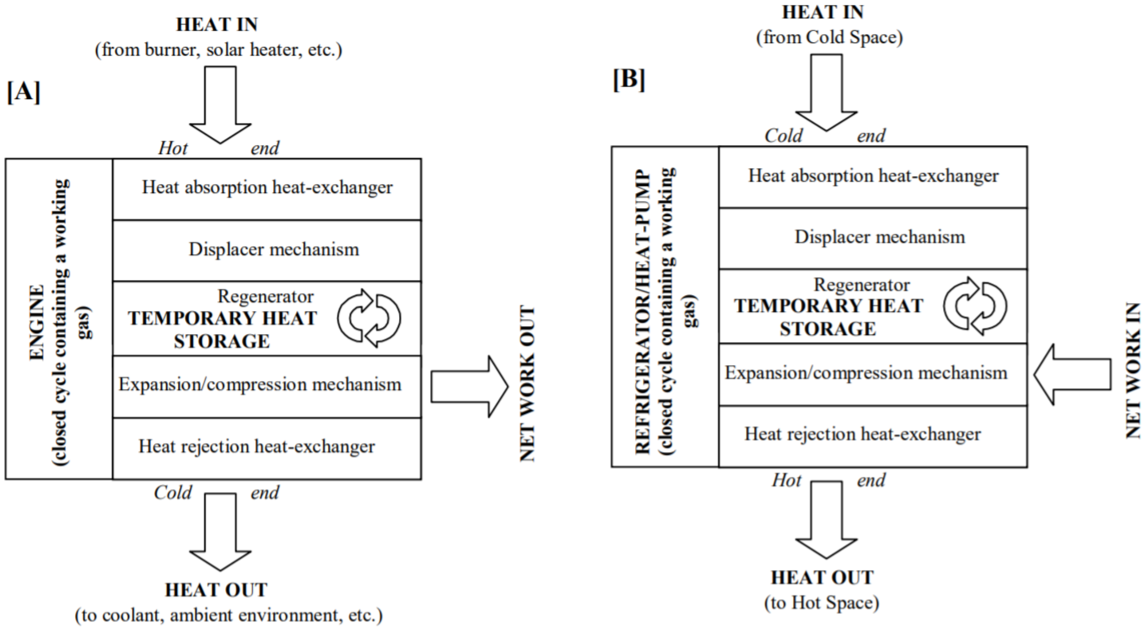

Figure 9. Stirling-cycle machine block diagrams: (A) Engine, (B) Refrigerator or heat-pump [7]

5.3 Solar energy

Another heat source we can use is the solar energy. The engine can be placed at the focus of a parabolic mirror that concentrates the radiation on it, being this radiation the heat source. While photovoltaic cells convert only 10% to 20% of the radiation in electrical energy, Stirling solar prototypes have efficiencies up to 30%. This way, the same amount of energy that is currently obtained with photovoltaic cells can be generated using less physical space. A prototype of this device is shown in the figure below.

Figure 10. Parabolic mirror with a Stirling engine on its focus

5.4 Automobiles

Due to the current environmental problems and to the fact that, sooner or later, fossil fuels will not be available or economical feasible to use any more, the internal combustion engines are being substituted by electrical and hybrid engines. Despite the Stirling engine not being relevant for a wide range of engine applications, because of its slow start and response to changes, it may still have a chance to be a success in the hybrid vehicles industry. Currently, these vehicles have an internal combustion engine that moves the car and charges the batteries. However, other alternatives are being developed where the propulsion of the car is electrical, and an engine connected to a generator is used to charge batteries. This engine can be a Stirling engine, since it is more silent and simpler than an internal combustion engine, and it can be working continuously at its maximum efficiency conditions while the batteries act like the regulator of the vehicle's power. This way the required amount of fuel would be reduced.

6. Engine parts

In this section of the report, the parts of the engine will be described. Since the engine was constructed as part of a previous bachelor thesis, pictures and descriptions from previous reports have been used to write this section [2] [3].

The figure below shows a drawing of the engine studied in this report with the names of its main parts.

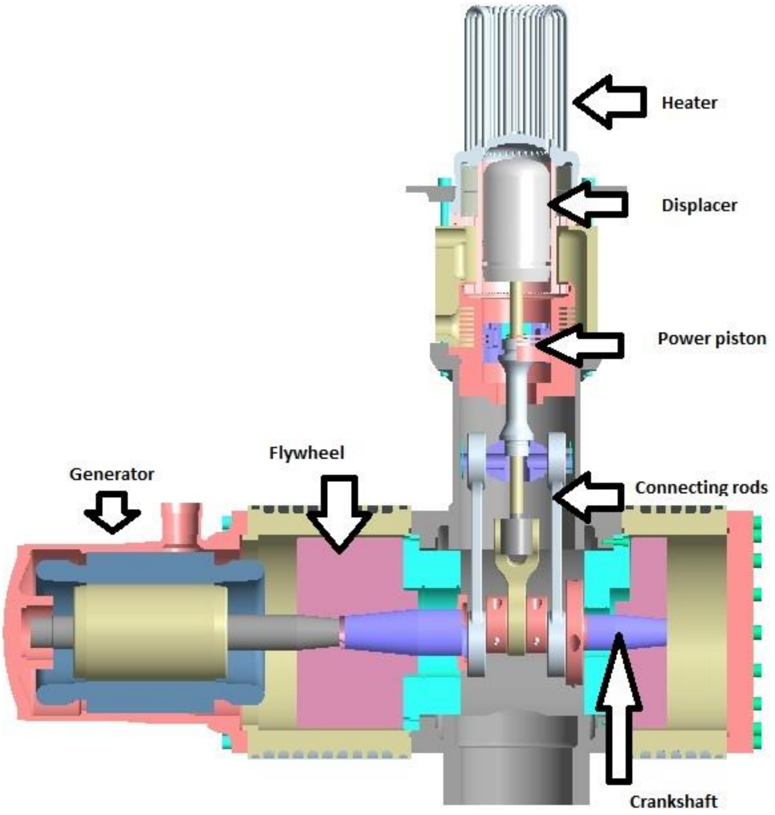

Figure 11. Engine overview [2]

Crankcase

As its name says, it is the housing of the crankshaft, and connects every part of the engine. It is fitted on a frame that allows the engine to stand on a plane surface.

At the bottom of the crankcase there is a cap, the “bottom cap”, which has some openings that can be used to fill gas or measure pressure. This is the piece that will have to be removed in order to change the crankshaft.

On the upper part there are inspection holes that can also be used to fill gas or measure pressure.

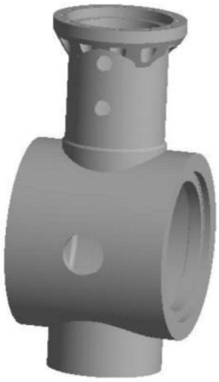

Figure 12. Crankcase

Figure 13. Bottom cap

Two bearing covers are mounted on the crankcase, one in each side. The bearings that support the crankshaft are placed in the centre of these covers.

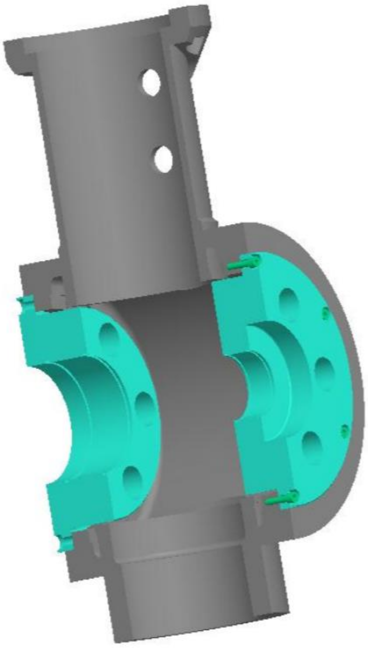

Figure 14. Bearing covers
mounted on the crankcase

Crankshaft

Its purpose is to transfer the mechanical work produced during the Stirling cycle to the generator, in order to transform it in electrical energy.

Figure 15. Crankshaft

This work is transferred from the piston to the crankshaft by three connecting rods, one small in the middle connected to the displacer and two larger on the sides connected to the power piston. The middle connecting rod moves with approximately 90º phase angle from the two other connecting rods.

Figure 16. Small connecting rod

Figure 17. Large connecting rod

To ensure its correct situation on the crankshaft four guiding rings are used (See Figure 18).

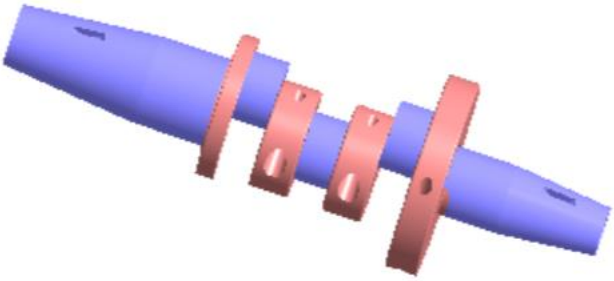

Figure 18. Guiding rings in the crankshaft

Figure 19. Guiding ring

Power piston

As said before in this report, the power piston transfers the power generated in the cycle to the crankshaft. It is bolted with a crosshead, and this is mounted on the two large connecting rods.

As shown in Figure 21, it is hollow in the middle so that the displacer rod can go through it.

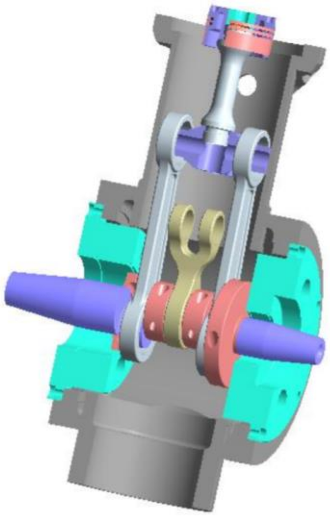

Figure 20. Power piston mounted on connecting rods

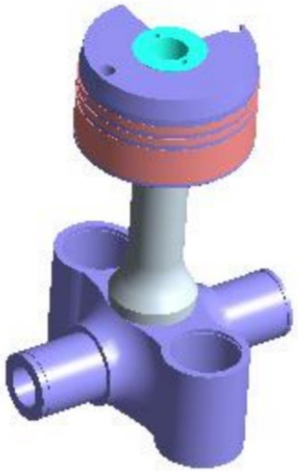

Figure 21. Power piston mounted on crosshead

Displacer

The displacer moves the working gas between the hot end and the cold end of the cylinder. It is mounted on a rod, which goes through the hollow section of the power piston. The rod is fitted on the small crosshead, and the crosshead is mounted on the small connecting rod.

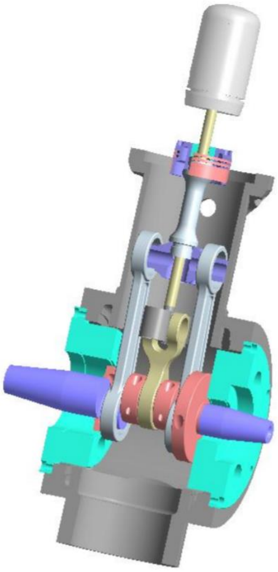

Figure 23. Displacer, displacer rod and small crosshead mounted on connecting rod

Figure 22. Displacer and displacer rod mounted on crosshead

Cold cylinder

The cold cylinder is placed on the top of the crankcase. It has around it the cooling jacket, which has an entry and an exit for the cooling water. This water flows between them and cools the engine.

Figure 25. Cooling jacket

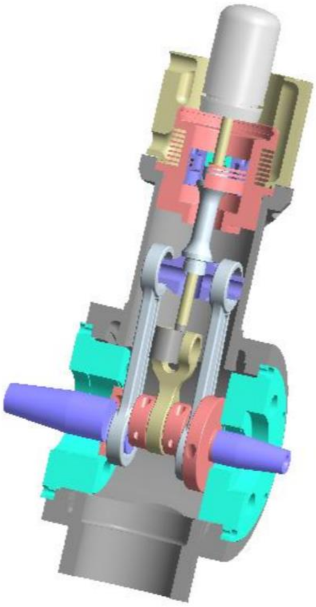

Figure 26. Cold cylinder and cooling jacket fitted on the engine

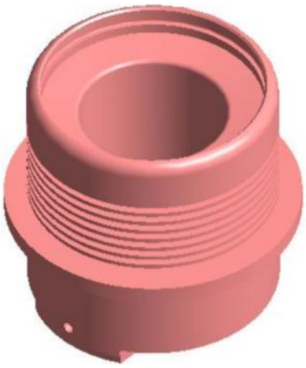

Figure 24. Cold cylinder

Hot cylinder

The hot cylinder is mounted on the top of the cold cylinder, inside the cooling jacket. There are 230 small pipes around it where the working fluid flows through, and the cooling water flows on the outside of them.

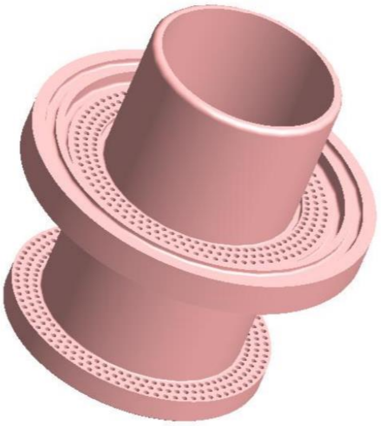

Figure 27. Hot cylinder

Regenerator

The regenerator is mounted on the top half of the hot cylinder. It consists of two rings with perforated metal inside that stores the heat when the working gas flows through it from the hot end to the cold end and preheats it again when it flows in the other direction.

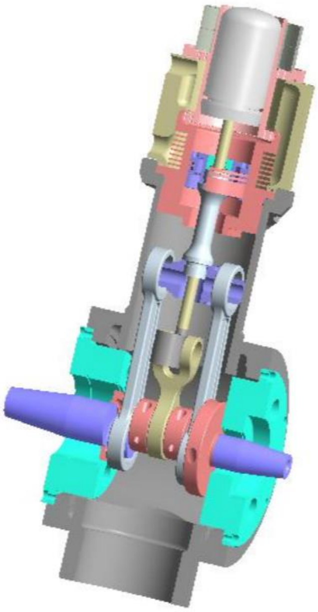

Figure 28. Regenerator mounted on hot cylinder

Figure 29. Regenerator

Cylinder top

The cylinder top is where the working gas gets heated up. This is done by heating the 50 tubes standing out of the cylinder top with the fluid inside. It is heated with a propane burner.

Figure 30. Cylinder top

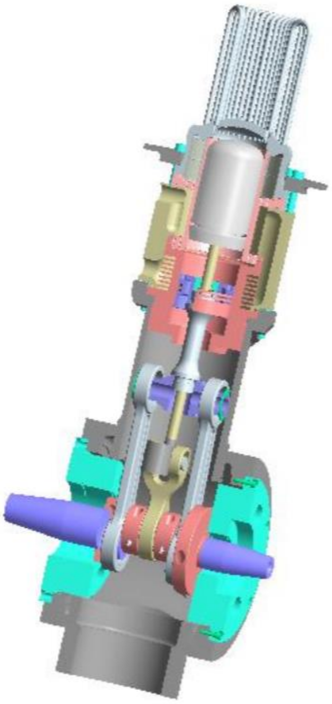

Figure 31. Cylinder top mounted on the engine

Generator

The generator consists of a stator, a rotor and the generator shaft. When the rotor spins inside the stator, it produces electricity. The generator shaft is connected to the crankshaft by the flywheel, and the flywheel is surrounded by the generator spacer.

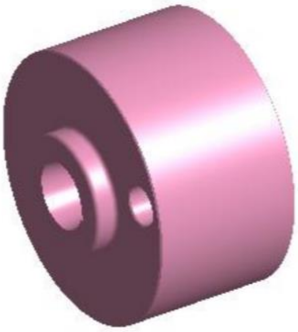

Figure 32. Flywheel

Figure 33. Generator spacer

The rotor is mounted on the generator shaft, and the stator inside the generator housing.

On the outside the generator housing has an electric power outlet and a cooling jacket where cooling water can flow in and out.

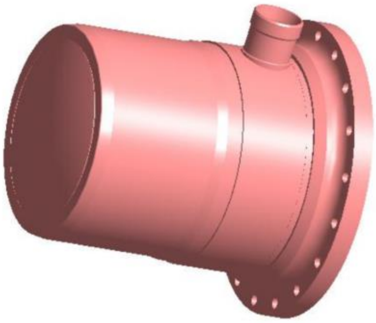

Figure 34. Generator housing

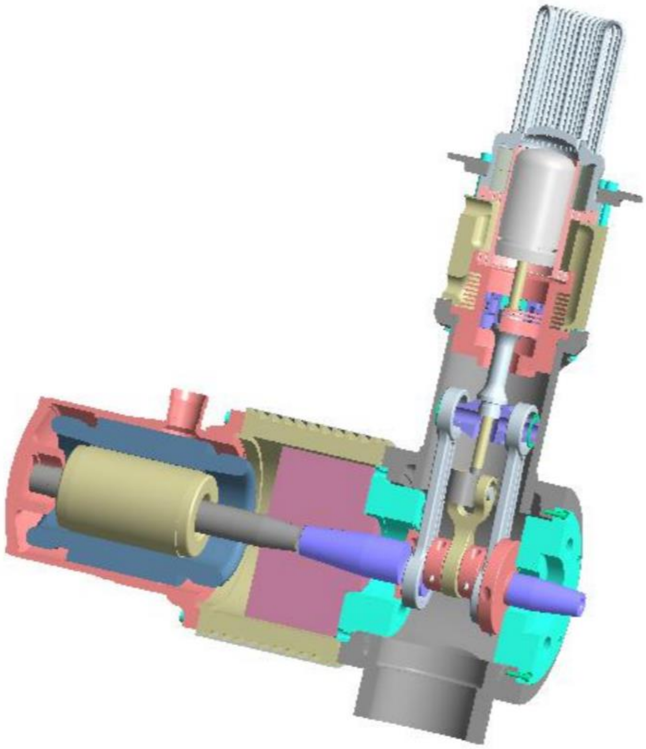

Figure 35. Generator in the engine

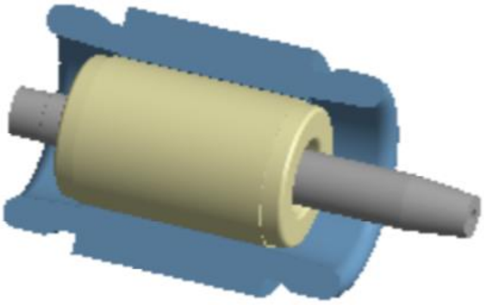

Figure 36. Generator

Counterweight

The counterweight is placed on the opposite end of the crankshaft. Its main function is balancing the engine when it is running.

Figure 37. Counterweight

The counterweight housing consists of three parts: a spacer, a cap and a metal plate surrounding the spacer allowing the cooling water to flow around it.

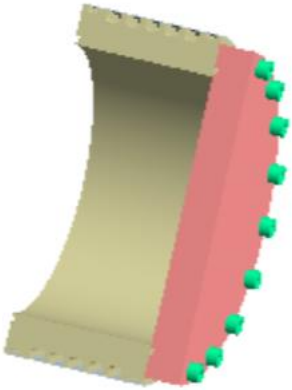

Figure 38. Counterweight housing

7. Preparation for testing

In 2013 a test station was set up for tests of the engine, and the same station has been used for the tests in this project. It consists of pressure and temperature sensors, a scale for measuring fuel consumption, and a frequency converter where the output from the generator can be read.

The plan for the measurements has been the same as in 2013: measure the highest temperature of the helium, temperature in and out of the cooling water, the mean pressure in the expansion cylinder and the back pressure in the crankcase, power, mass flow on the cooling water, and fuel consumption.

In addition, the burner and the cooling system, which has been described in the section before, are fitted onto the engine.

7.1 Helium filling

In order to see if there are any leakages in the engine, it is tested with nitrogen first. No leaks were found. However, helium atoms are smaller than nitrogen molecules. After checking that the engine does not have big leakages, it was important to check that there are not small ones either. This was done by filling it with helium, making marks in the manometers and then waiting for a week. If the pressure had decreased over the course of a week, it would have pointed towards leakages.

To fill it with helium, it was first necessary to empty it completely. A vacuum pump was used to do this, as shown in Figure 39. The engine is completely empty when the manometers show between 0 and -1 bar (the manometers show gauge pressure).

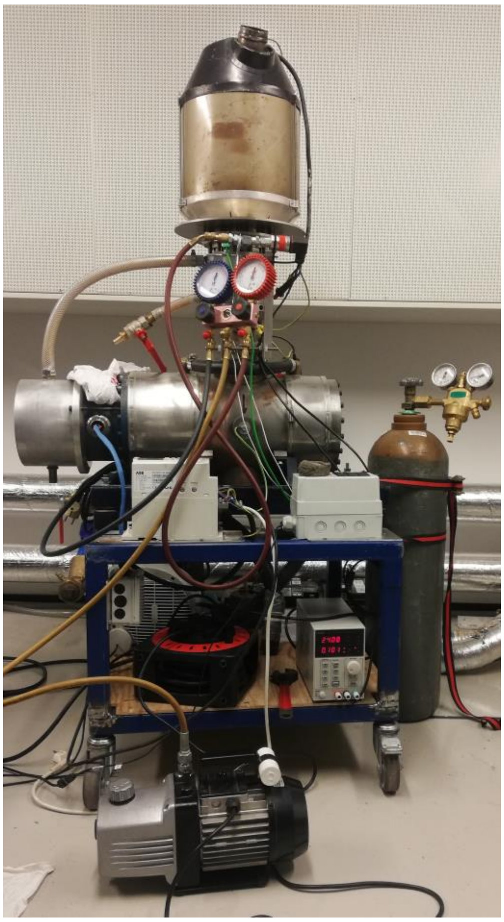

Figure 39. Vaccum pump (at the bottom) connected to the engine

After this, the engine was filled with helium. First, we closed the valves on the manifold, and the end of the yellow hose, which was connected to the vacuum pump, was removed and connected to the helium container (see Figure 41).

Then the helium regulator is opened and the blowback valve pin in the manifold is pressed and held for a few seconds in order to evacuate all the air in the hose, as shown in Figure 40.

The hood that previously was removed is fastened back onto the manifold and, after setting 40 bar in the regulator, the main valves are opened, letting helium fill the engine. Finally, the valves are closed again.

Figure 40. Evacuating air from the yellow hose

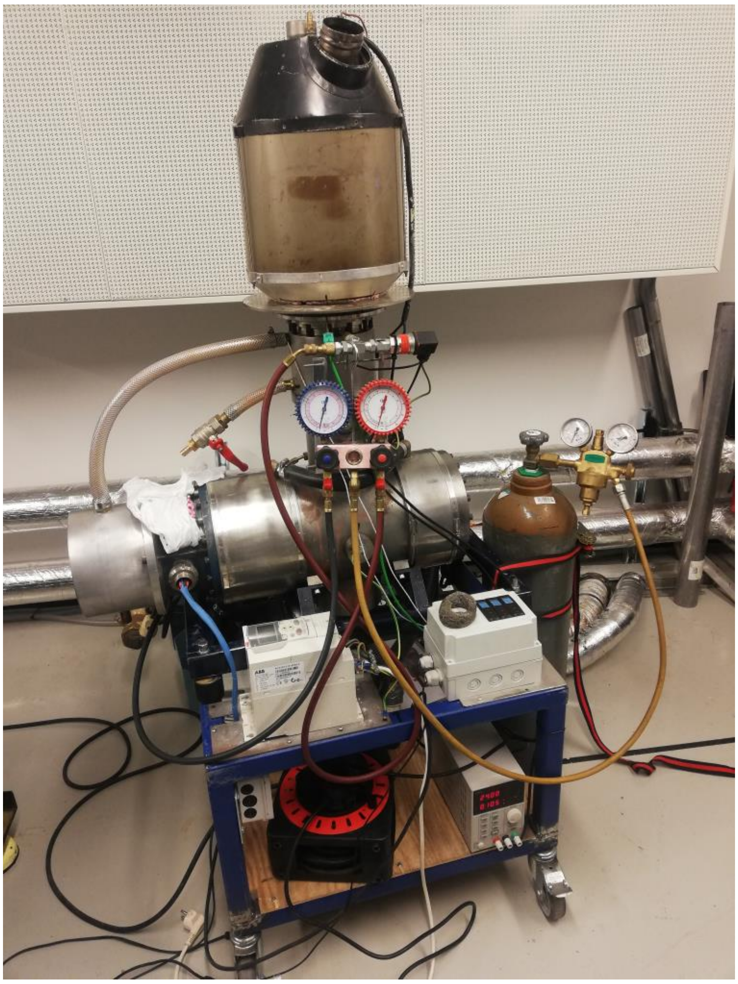

Figure 41. Engine connected to the helium container (on the right of the image)

8. High ΔT operation

After following the procedure described in the previous section, the engine could be started.

The first step was to start the cooling so that any damage due to overheating was prevented. A small leakage of water was in the cooling system. This did not affect the operation of the engine and measurements could be taken.

The heat source was activated in the next step. There is a piezoelectric starter that was supposed to be used to ignite the propane. However, it was not working properly. It has been placed in some different locations inside the burner to try to make it work better, but without success. The propane was ignited with manually with a torch instead.

Once the heating had been turned on, the last step was to use a frequency converter to set an appropriate frequency for the engine revolutions. All the measurements in this section have been taken at 1500 rpm.

When the engine started turning, it showed strong vibrations that could be a problem to take the measurements properly and had the potential to destroy parts of the engine. However, the vibrations were weaker at higher speeds and the engine operated more stably. There were no problems to take the measurements at 1500 rpm. These vibration problems could be due to a faulty mounting of the counterweights by the previous groups. This would not be clear until the engine was disassembled in order to change the crankshaft.

The procedure followed to take the measurements and the values obtained can be found in Attachment 1.

8.1 Performance test

A performance test has been carried out to map out the electrical power output as a function of pressure and temperature. The engine has been tested at 30 bar, 35 bar and 40 bar of pressure and 650ºC, 700ºC and 750ºC of temperature.

8.1.1 **Test results**

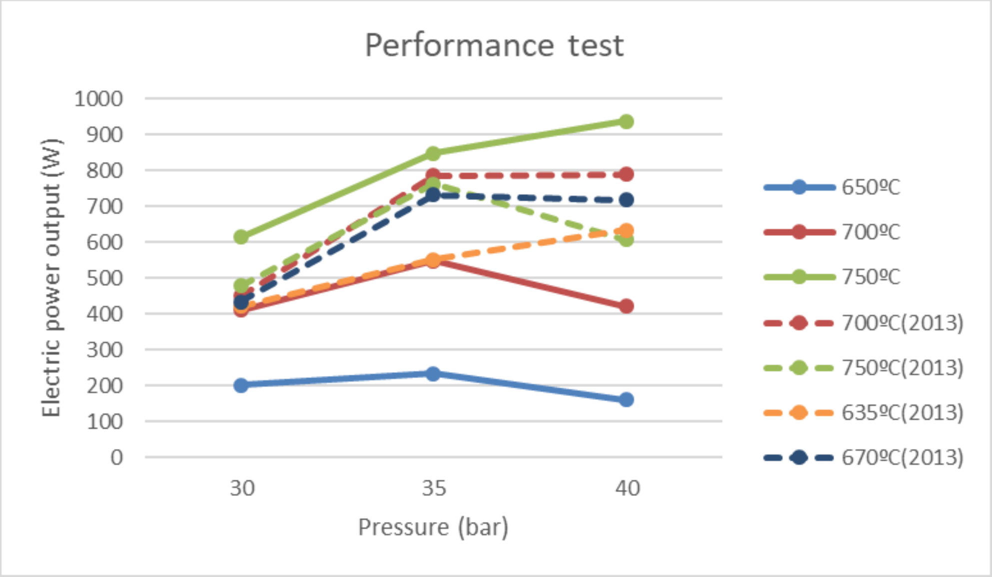

Figure 42. Electric power output

¡Error! No se encuentra el origen de la referencia. shows the results for the tests carried out this year and the results from 2013 for the same temperatures in the burner.

The complete data and the calculations made in order to draw the graph can be found in Attachment 2.

8.1.2 Discussion

As we can see in the graph, in both tests (2013 and 2019) the power tends to be higher for 35 bar, but in the last tests the value of the power for 40 bar and 750ºC is much higher than expected. Since this was the first measurement that was taken and there were a lot of problems with vibrations in the beginning of the tests, a possible explanation for this is that the engine had not stabilized yet.

In 2013 the engine was run and tested two times, obtaining better results in the second tests according to their report [3]. This year it has been tested only one time and just at three different temperatures. This and the fact that the engine has not been used for six years affect to the accuracy of the results.

In order to make a comparison more accurate, the deviations between 2013 and 2019 have been calculated with this formula:

$$Deviation(\%) = \frac{\dot{W}_{\mathrm{el,2019}} - \dot{W}_{\mathrm{el,2013}}}{\dot{W}_{\mathrm{el,2013}}} \cdot 100$$

and these are the results:

	Temperature / ºC	
Pressure / bar	**700ºC**	**750ºC**
30	-8.45%	28.48%
35	-30.24%	11.20%
40	-46.69%	54.57%

In 2013 tests the power is lower for low temperatures and when the temperature increases the power remains more or less constant. However, this does not happen in the last tests. In 2019 tests the power at 650ºC is much lower than in 2013, and it increases for 750ºC reaching higher values than in 2013.

The response of the engine at 650ºC and 700ºC is not what was expected, since the power is much lower than in 2013, but the low values make sense due to the long time it was not used and the broken bearings that caused vibrations. However, the values for the power obtained this year at 750ºC are much higher than the values in 2013, what does not make sense.

To sum up, for all the reasons before mentioned, such as the vibrations and the long time when the engine was not used, and due to the unexpected delays and problems with the engine, probably some of the measurements are mistaken, what would explain the results obtained in the tests.

8.2 Schmidt analysis

Schmidt analysis will be used for analysing the measured data. In order to do that the excel file used in the previous report will be used. This excel file uses the measured upper and lower temperatures, as well as the pressure in the engine to calculate the theoretically obtainable delivered power. The formulas are the same used in the previous report [3], and they are in Attachment 3 along with the constant values used in the analysis.

8.2.1 Theoretical approach

The Schmidt theory is one of the isothermal calculation methods for Stirling engines. It is based on the isothermal expansion and compression of an ideal gas.

The principal assumptions of Schmidt's analysis of Stirling cycle engines are:

1. All processes are reversible.
2. The regeneration process is perfect.
3. The working fluid obeys perfect gas law, PV = mRT.
4. The mass of air in the system remains constant.
5. The volume variation in the working space is sinusoidal.
6. There is no temperature gradient in the heat exchanger.
7. The speed of the machine is constant.
8. Steady state conditions are established.
9. Temperatures in heater, cooler and regenerator are isothermal.

8.2.2 Test results

The first table shows the theoretical results and the second one shows the measurements.

Results	Units	Test 1	Test 2	Test 3
Thermodynamic Carnot Efficiency		0.725	0.726	0.727
Pressure, P_m	[bar]	30	35	40
Work per cycle	[J/rev]	134.2	157.1	180.0
Speed, n	[rpm]	1500	1500	1500
	[rps]	25	25	25
Indicated power, $P_{i,\,ut}$	[W]	3354.14	3927.37	4499.58
	[kW]	3.35	3.93	4.50
Power output on shaft, P_b	[kW]	1.27	1.48	1.69
Output power from generator	[kW]	1.02	1.18	1.35

	Units	Test 1	Test 2	Test 3
Pressure	[bar]	30	35	40
Nominal torque, T	[Nm]	20.17	20.17	20.17
Angle speed, ω		157.08	157.08	157.08
Speed, n	[rpm]	1500	1500	1500
Frequency, f	[Hz]	50	50	50

Results	**Units**			
Highest percent of nominal torque	[%]	19.4	26.8	29.6
Given torque	[Nm]	3.91	5.41	5.97
Output power from generator	[W]	614.6	849.1	937.8
	[kW]	0.61	0.85	0.94
Power on generator	**[kW]**	**0.77**	**1.06**	**1.17**

8.2.3 Discussion

As we can see, the actual power output is lower than the theoretical power output, something that was expected. However, what was not expected is the big difference between them. This difference is probably due to the assumptions that are made to do the calculations and cannot be accomplished in the real life, like the perfect regeneration or the isothermal processes. Another thing that can affect is the fact that is an old engine that has not been used for several years. The same happened in 2013, probably for the same reasons before mentioned. For all these reasons, we can conclude that the engine needs to be improved, as well as the theoretical model. In order to reach this objective, some suggestions will be explained in the conclusion of the report.

9. Change of the crankshaft

First of all, the working gas needed to be removed from the engine, following the same procedure that was followed to empty it for the first time.

Then all the measurement instruments were removed, as well as the exhaust gas system of the burner.

After this, the generator housing, the counterweight housing and the counterweights were removed, as well as the end cover of the crankshaft housing.

The next step was to remove all the pieces that are mounted in the crankshaft, which was quite difficult because it had to be done from the bottom of the engine. These pieces are the guiding rings and the connecting rods. It has been in this step where the reason for the vibrations was found out. Some of the bearings that connect the crankshaft with the connecting rods were broken. This did not allow for the movement to be transmitted properly.

Next thing to be done was inserting the new crankshaft into the engine. However, the guiding rings did not fit (see Figure 43). This was not expected.

It has not been possible to get the new ones either manufactured in house or ordered and delivered in time, so that the crankshaft could be mounted on the engine and the second measurements carried out.

For this reason, it will be explained in the following sections how the engine is supposed to operate with low ΔT and the further work to be done with the engine in order to make the desired measurements.

Figure 43. Guiding ring in the new crankshaft

10. Low ΔT operation

Since it was not possible to test the engine in these conditions, a little research has been done about how the low ΔT Stirling engines work and possible applications for them.

A low temperature differential (LTD) Stirling engine can be run with small temperature difference between the hot and cold ends of the displacer cylinder.Some of its characteristics [4] are:

1. Displacer to power piston swept volumes ratio is large
2. Diameter of displacer cylinder and displacer is large
3. Displacer is short
4. Displacer stroke is small
5. Operating speed is low

In the engine analysed in this project the plan was to change the crankshaft for another with a reduced stroke, reducing this way the displacement volume, the compression and the optimal number of revolutions per minute.

They become of interest when considering the possibility of power generation from many low temperature waste heat sources, because in these cases they can use free or cheap low temperature sources.

A potential heat source that can be used is the solar energy, providing the possibility of direct conversion of solar energy to mechanical work [5]. Another possibility is to use them for waste heat recovery. As explained in previous sections, the waste heat from the industry can be used as a heat source.

11. Conclusion

As it was said before, the original plan for the project could not be carried out. Because of this, it is not possible to make the comparison between the high temperature response and the low temperature response of the engine, which was the main objective of the project.

However, the engine still works, and it is ready to be modified, so this can be the bachelor thesis of future students of mechanical engineering. It would be very interesting to have an operative Stirling engine for the department's work and research within the field of waste heat recovery and energy efficiency, as well as practical thing for students to do work on.

In Further work section it is explained what needs to be done in order to carry out the tests with low temperature heat source.

11.1 Further work

The crankshaft could not be changed because the guiding rings did not fit on it. The first thing to do will be ordering the new ones, so that the new crankshaft can be placed in the engine. Since some of the bearings that were in the engine were damaged, it is also necessary to check that the new ones are available.

Once the crankshaft is in its place and the engine is assembled again, it must be tested in low ΔT operation. The results obtained in these tests must be compared with the results obtained when the engine was tested in high ΔT operation, in order to find out how these changes affect the output power of the engine.

In addition, the department's 3D scanner can be used to create a model of the new crankshaft. There are not available drawings of it, so would be interesting to have it and use it for the development of the new pieces that need to be made.

Another thing that can be implemented is an advanced Stirling engine model, more accurate than the Schmidt analysis, in order to compare it with the actual engine.

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List of figures

Attachment 1

The temperature has been regulated by changing the amount of propane and the amount of air that go into the burner.

In order to regulate the pressure in the engine, it is enough to let helium go out of the engine until the manometer marks the desired pressure. Since the helium is not flammable, it is not necessary to turn off the burner.

Measurements at 40 bar

Voltage (V)	Current (A)	T_{burner} (ºC)	$T_{water,in}$ (ºC)	$T_{water,out}$ (ºC)	O_2 (%)	Torque (%)
208-210	6.1	761.9	9.4	15.6	13.4	29.6
208-210	5.4	704.4	9.1	14.6	15.2	13.3
208-210	5.1	652.8	9.0	14.7	15.7	5.1

Measurements at 35 bar

Voltage (V)	Current (A)	T_{burner} (ºC)	$T_{water,in}$ (ºC)	$T_{water,out}$ (ºC)	O_2 (%)	Torque (%)
208-210	6.0	756.4	8.7	14.9	13.7	26.8
208-210	5.5	703.8	8.7	14.8	15.4	17.3
208-210	5.2	650.6	9.0	13.9	15.8	7.4

Measurements at 30 bar

Voltage (V)	Current (A)	T_{burner} (ºC)	$T_{water,in}$ (ºC)	$T_{water,out}$ (ºC)	O_2 (%)	Torque (%)
208-210	5.6	753.6	9.1	14.7	15.2	19.4
208-210	5.4	701.4	9.3	14.9	15.7	13
208-210	5.1	654.1	9.0	14.7	16	6.4

Attachment 2

In this table are shown the values of the fraction of the nominal torque the engine is delivering.

	Temperature / °C		
Pressure / bar	**650**	**700**	**750**
30	0.064	0.13	0.194
35	0.074	0.173	0.268
40	0.051	0.133	0.296

In order to calculate the values in the next table, the next formula was used:

$$\dot{W}_{\mathrm{el}} = \eta_{\mathrm{torque}} \tau_{\mathrm{nominal}} \nu \pi$$

Where η_{torque} are the values from the first table; τ_{nominal} is the nominal torque, which is 20.17 N·m according to the previous report; and ν is the frequency of the voltage the generator delivers, which value is 50 Hz.

As a result of these calculations, the values for the electric power output are obtained.

	Temperature / °C		
Pressure / bar	**650**	**700**	**750**
30	202.668	411.670	614.338
35	234.335	547.837	848.673
40	161.501	421.170	937.340

These are the values represented in the graph.

Attachment 3

Constants

Swept expansion volume: Vse = 500 cm^3

Swept compression volume: Vsk = 500 cm^3

Expansion dead volume: Vde = 200 cm^3

Compression dead volume: Vdk = 200 cm^3

Regenerator volume: Vr = 200 cm^3

Gas constant: R_{He} = 2,0769 kJ/(kg*K)

Specific heat capacity at constant pressure: $c_{p,\,He}$ = 3,1156 kJ/(kg*K)

Specific heat capacity at constant volume: $c_{v,\,He}$ = 5,1926 kJ/(kg*K)

k = 1,667

Faseforskyvning: φ = 90° = π/2 rad

Formulas

Temperature Difference: $\Delta T = T_H - T_L$

Thermal efficiency: $\eta_{th} = T_L/T_H$

Carnot efficiency: $\eta_{carnot} = 1 - T_L/T_H$

Second law efficiency: $\eta_{II} = \eta_{th} / \eta_{carnot}$

Average effective temperature in regenerator: $T_r = \frac{T_H - T_L}{\ln(\frac{T_H}{T_L})}$

$$X_b = \frac{V_b}{V_{se}}$$

Dead volume: $V_d = V_{de} + V_{dk} + V_r$

Hub volume ratio: v = $\arctan\left(\frac{V_{sk} \cdot \sin(\varphi)}{V_{se} - V_{sk} \cdot \cos(\varphi)}\right)$

$$T_d = \frac{V_{de} + V_r + V_{dk}}{\frac{V_{de}}{T_H} + \frac{V_r}{T_r} + \frac{V_{dk}}{T_L}}$$

Reduced dead volum: $s = \frac{V_d \cdot T_L}{V_{se} \cdot T_d}$

$$A = \sqrt{t^2 - 2 \times t + 1 + 2(t-1) \times v \times \cos(\varphi) \times v^2}$$

$$B = t + 1 + v + 2 \times s - 2 \times X_b$$

$$\Delta = arctan\left(\frac{v \times \sin(\varphi)}{t - 1 - v \times \cos(\varphi)}\right)$$

$$c = \frac{A}{B}$$

$$V_e = 0.5 \times (V_{se} + V_{sk})$$

$$V_c = 0.5 \times V_{se} \times (1 - \cos(\alpha))$$

$$V_b = 0.5 \times (V_{se} + V_{sk}) - \sqrt{\frac{1}{4} \times \left({V_{se}}^2 + {V_{sk}}^2\right) - 0.5 \times V_{se} \times V_{sk} \times (\cos(\alpha))}$$

$$V_{tot} = V_e + V_c + V_r$$

$$m_{tot} = \frac{P_m \times V_{se} \times (B - A \times \cos(\alpha - \Delta))}{2 \times R \times T_L}$$

$$P = \frac{P_m \times \sqrt{1 - c^2}}{1 - c \times \cos(\alpha - \Delta)}$$

$$P_{maks} = \frac{P_m \times \sqrt{1 - c^2}}{1 - c}$$

$$P_{min} = \frac{P_m \times \sqrt{1 - c^2}}{1 + c}$$

$$W_{Schmidt} = \frac{P_m \times V_{se} \times \pi \times c \times (1 - t) \times \sin(\Delta)}{1 + \sqrt{1 - c^2}}$$

$$P_{i,ut} = W_{Schmidt} \times \frac{n}{60}$$

$$P_b = P_{i,ut} \times \eta_{II}$$

Schmidt analysis

	Units	Test 1	Test 2	Test 3
Pressure, P_m [Pa]	[Pa]	**3000000**	**3500000**	**4000000**
	[bar]	**30**	**35**	**40**
Temperature heater, T_H [K]	[K]	**1026.6**	**1029.4**	**1034.9**
Temperature cooling, T_L [K]	[K]	**282.1**	**281.7**	**282.4**
ΔT [K]	[K]	**744.5**	**747.7**	**752.5**

Beale-factor		**0.0071**	**0.0071**	**0.0071**
Optimal Beale-factor		**0.0150**	**0.0150**	**0.0150**
Deviation	[%]	**52.4**	**52.5**	**52.5**

Thermal efficiency		**0.275**	**0.274**	**0.273**
Carnot efficiency		**0.725**	**0.726**	**0.727**
Second law efficiency		**0.379**	**0.377**	**0.375**
Generator efficiency		**0.8**	**0.8**	**0.8**

Results	**Units**	**Test 1**	**Test 2**	**Test 3**
Thermodynamic Carnot Efficiency		**0.725**	**0.726**	**0.727**
Pressure, P_m	[bar]	**30**	**35**	**40**
Work per cycle	[J/rev]	**134.2**	**157.1**	**180.0**
Speed, n	[rpm]	**1500**	**1500**	**1500**
	[rps]	**25**	**25**	**25**
$P_{i, ut}$	[W]	**3354.14**	**3927.37**	**4499.58**
	[kW]	**3.35**	**3.93**	**4.50**
P_b	[kW]	**1.27**	**1.48**	**1.69**
Delivered power from generator	[kW]	**1.02**	**1.18**	**1.35**

Constant data

Displacement expansion, Vse [m3]	[m3]	**0.000118578**	**0.000118578**	**0.000118578**
Displacement compression, Vsk [m3]	[m3]	**0.000122458**	**0.000122458**	**0.000122458**
Dead Volume expansion, Vde [m3]	[m3]	**0.000013175**	**0.000013175**	**0.000013175**
Dead volume compression, Vdk [m3]	[m3]	**0.000004771**	**0.000004771**	**0.000004771**
Regenerator volume, V_r [m3]	[m3]	**0.00001**	**0.00001**	**0.00001**
Phase offset, φ	[deg]/[rad]	**90˚**	**1.5708**	**1.5708**
Crankangle, α	[deg]/[rad]	**0˚**	**0.0000**	**0.0000**

Gas constant	[J/(kg*K)]	**2076.9**	**2076.9**	**2076.9**
Specific heat capacity, c_v	[J/(kg*K)]	**3115.6**	**3115.6**	**3115.6**
Specific heat capacity, c_p	[J/(kg*K)]	**5192.6**	**5192.6**	**5192.6**
Specific heat conditions, k		**1.6666**	**1.6666**	**1.6666**
T_r	[K]	**576.4**	**577.0**	**579.4**

Temperature ratio, t		**0.3**	**0.3**	**0.3**

X_b		**0.2976**	**0.2976**	**0.2976**
Hub Volume ratio, *v*		**0.8015**	**0.8015**	**0.8015**
V_d	[m3]	**0.000027946**	**0.000027946**	**0.000027946**
T_d	[K]	**593.4**	**593.8**	**596.1**

Decreased dead volume, s		**0.112**	**0.112**	**0.112**
A		**0.725**	**0.726**	**0.727**
B		**1.705**	**1.704**	**1.703**
Δ		**-0.835**	**-0.835**	**-0.834**
c		**0.425**	**0.426**	**0.427**
V_e	[m3]	**0**	**0**	**0**
V_c	[m3]	**0.00009**	**0.00009**	**0.00009**
V_b	[m3]	**0.00004**	**0.00004**	**0.00004**
V_{tot}	[m3]	**0.00010**	**0.00010**	**0.00010**
m_{tot}	[kg]	**0.000369951**	**0.000431238**	**0.000490852**
P	[Pa]	**3799275.183**	**4435996.174**	**5072462.531**
P_{maks}	[Pa]	**4724453.3**	**5519037.449**	**6313107.793**
P_{min}	[Pa]	**1904982.318**	**2219589.94**	**2534409.442**