Bachelor's theses in mechanical engineering

The thermodynamics of the GREC version 3

Investigation of engine performance and energy conversion

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Abstract

The GREC (Green Revolution Energy Converter) is a new concept of a heat engine invented by nilsinside AB. The goal of this engine is to reduce the waste heat in industries by using waste heat to create mechanical energy. Its main function is to create a pressure difference when a working volume is rotated to a hot and cold side. The advantage of this engine is that it can be scaled to be both smaller or bigger, depending on it's power demand.

The goal of this project is to build a functioning prototype of the GREC with a measurable pressure difference. More specific goals of this report is to investigate how the pressure difference can be converted to mechanical energy using a piston. Calculating the work and power of the engine is also of interest to compare the prototype to theory.

Conclusions regarding materials can be drawn showing that Fiber Reinforced Plastic is a good material for the insulating fins and Rotating shutter and aluminium is good for the conducting fins. The engine has not been tested yet so conclusions regarding performance of the engine can not be drawn. Future work of this project could be to implement a piston to convert the energy using the results of this project to set the dimensions of the piston.

Distribution of work

This chapter presents rough estimations of how much work has been carried out by each group member for each respective part of the project.

Activity	**Johan**	**Vidar**	**Jakob**	**Comment**
Planning	33%	33%	33%	WBS and GANTT
Theory research	33%	33%	33%	
Work carried out in:				
Concept generation	33%	33%	33%	
CAD	35%	60%	5%	Supported construction group
Analysis	30%	30%	40%	
Writing:				
Introduction	33%	33%	33%	
Theory	30%	25%	45%	
Method	45%	30%	25%	
Results	25%	35%	40%	
Discussion	40%	30%	30%	
Conclusion	33%	33%	33%	

Contents

Nomenclature

BDC Bottom dead centre

FRP Fiber reinforced plastic

$GREC$ Green Revolution Energy Converter

HTC Heat transfer coefficient

RS Rotating shutter

TDC Top dead centre

WGV Work generating volume

1. Introduction

This chapter consists of background information regarding the conception of the GREC engine and its basic function. The chapter also includes the work carried out in previous projects and studies.

1.1 Environment

Today the world is facing big problems regarding emissions of green house gases which speeds up the global warming. Many existing industries emit much waste heat that our modern technology cannot convert to usable energy. According to the EU, Between 20 and 50% of the energy used in industries is lost through waste heat. [1] There is clearly room for improvement regarding energy and heat efficiency in industry processes.

The GREC (Green Revolution Energy Converter) is a new concept of a thermal engine. It resembles a Stirling engine in that it converts heat differences to mechanical power. A benefit of the GREC is the potential of using industrial heat waste to power the engine. This allows for reduction of waste heat in big processes, increase in overall process efficiency whilst having no added emissions. [2]

1.2 Company

nilsinside AB is a company focusing on research and development of sustainable energy recovery based in Sweden. The main focus is on development of the GREC engine, an invention by the founder Nils Karlberg to which they hold multiple patents. This technology aims to reduce energy loss due to excess heat from other processes. Technology Readiness Level (TRL) is a system which defines at what state a technology is at on a scale between 1 and 9. A lower rating indicates a more research level project while a higher rating indicates a technology that is closer to being sold to customers. At this point, the GREC has a rating between 3 and 4. The next step in the development process is to create a functioning prototype to test the GREC engine in reality. [2]

1.3 Technology behind GREC

The GREC works according to the Carnot cycle, where a fluid is heated so that it expands. Work can be extracted from this expansion and thus energy can be produced. A GREC engine achieves this by moving a fluid from a heating zone to a cooling zone. The fluid is moved by a revolving shutter(RS), which is a disc with a section cut out. The volume of this section is what makes up the Work Generating Volume (WGV). The fluid is heated and cooled by conducting fins. These are put on opposite sides of the GREC so that the only heat transfer between these is from the convection of the fluid. There are insulating fins between the conductive fins to prevent heat leaking from the hot side to the cold side. Figure 1 visualizes the motion of the RS and the temperatures of the fins in a simple way.

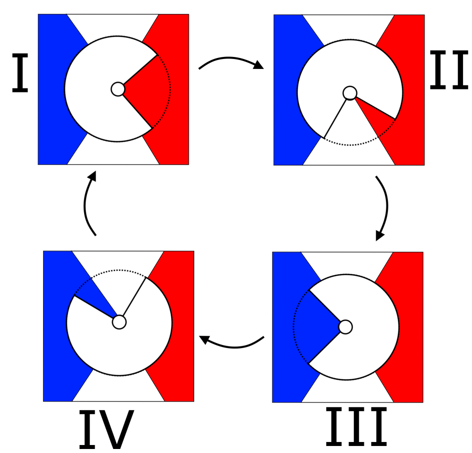

Figure 1: Simple visualization of the GREC-cycle. In step I the WGV is heated since the RS only exposes the fuild to the heating fins. In step II the WGV is in a transfer state between the hot and cold side. Between step I and II the pressure rises in the WGV and the theoretical piston begins it's power stroke. In step III the WGV is cooled and the piston begins it's return stroke with as little resistance as possible. In step IV the WGV is transitioning into the hot side and the pressure begins to rise once again as the RS starts to expose the heating fins and thereby completing the cycle.

The engine is stackable, meaning that more layers of RS and fins can be added to increase work output, see figure 2. The RS is actuated using an electric motor. Stacking of layers allows for a higher potential energy output but also results in more friction forces. This increases the demands for the electric engine and the engine efficiency. For the engine to work entirely as desired, the engine must extract more work from the pressure difference inside the engine than is used to run the electric motor. [3]

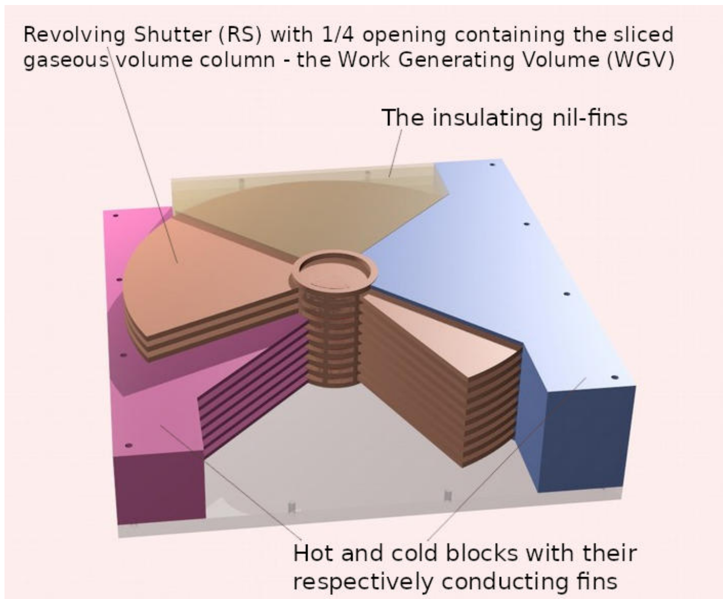

Figure 2: Cutout of the GREC, shows how several layers of RS can be used to increase the volume of the GREC engine.

1.4 Previous Work

The previous work for the GREC engine has been studied and written in three different projects. The first project was conducted in the spring of 2022 by five students from the Department of Management and engineering at Linköping University. Since this project set the foundation for the rest of the research of the GREC engine this will be one of the main basis for the study. The published result is called: Theoretical Proof Of Concept For The Green Revolution Energy Converter: Development of a mathematical model, material analysis and physical model improvements. [4] The main objectives from the study consisted of;

- Creating a proof of concept for the GREC engine

- Studying material selection for crucial parts of the engine
- Analyzing construction improvements from the initial design

Regarding the proof of concept the main results found were that high temperature differences between the heat sources is desired. This in order to achieve the highest possible power output and efficiency. The size of the engine was also found to be of interest, larger scales showed to be more effective and efficient at different temperatures.

The material selection studies were mainly performed for three engine parts, the conducting fins, the isolation as well as the revolving shutter. Copper was found to be the best material for the conducting fins when regarding effectiveness. However aluminium was also found to be a candidate when considering price. Fiber reinforced plastic was the clear choice for isolation material when considering it's thermal properties , performance and price. ABS 10% carbon fiber was found to be the best material for the revolving shutter since it provides low heat transfer within the material and has a high yield limit. Polysterene is considered to be viable at low rpm and temperature. Higher values for these parameters might cause the material to break so the reliability is limited. Polysterene is also five times less expensive than the ABS 10% carbon fiber.

The project "Investigation of the internal heat transfer of GREC", from a project course TMPE09 in the fall of 2022, studied how the design of the engine effects the pressure difference and work output. [5] Furthermore the project also investigated how turbulence in the WGV effected the pressure and work. The results indicated that a slow rotation speed of the RS and a thin WGV leads to a greater pressure difference within the WGV. Instead when the RS is rotating slowly the heat rate is increasing which results in a higher generated work output. To reach a high generated output it is concluded that a higher temperature difference between the hot and cold side is desired. Turbulence in the WGV also increases both the generated work and pressure difference. However the scope of the project was not to decide how the turbulence is created but only how it affects the heat transfer.

A design where 1/8 instead of 1/4 of the RS was cut out was also investigated where the results showed that the heat transfer increases with this design. A main conclusion from this project is that if a high temperature difference is possible a large rotating radius is desired. The detailed results for the achieved power from the different simulations and dimensions can be seen in table 1.

Table 1: Simulation results for different engine dimensions and rotor speeds. [5]

Simulation name	**Changed parameter**	**Simulation time [h]**	**Pressure diff. [kPa]**	**H-value** $[W/m^2K]$	**Power [W]**
Reference case		28	4,9	88,2	127
Low rotor speed	500 rpm	22	7,9	45,2	65,7
High rotor speed	3000 rpm	29	3,8	122,7	195,6
Short rotor radius	0,145 m	14	4,1	75,4	26,7
Long rotor radius	0,58m	50	6,8	114,4	709,9
Thin WGV	0,005m	18	7,6	87,3	123,3
Thick WGV	0,011	21	3,5	59,3	124,5
1/8 RS design	1/8	19	2,9	119,4	148,4
HTC optimizer	Optimized	27	5,2	96,0	136

The third project that has studied the GREC engine is "Thermal investigation of the Green Revolution Energy Converter" [6]. The goal of this project was to investigate the external heating to the conducting fins. A method called PHT where pipes was placed on the conducting fins filled with a fluid that is heating the fin. The other method was called NHPT where the heating fins was heated directly with conduction between a heating solid cylinder and the heating fin. The main conclusion drawn from this project was that the solution with pipes, PHT, was concluded better in terms of heat rate. However the scope of this project was not to take any constructions in reality in to account which is a limitation to our project since a prototype will be built in reality.

1.5 Project distribution

The project is distributed into three groups. The groups have different focus areas that are construction, mechatronics and thermodynamics. The studies conducted by this group mainly regard heat and fluid properties of the engine. All the groups have worked closely together and many aspects of the conceptualisation and design ideas for the engine have been realized by all groups together. This in order to make the engine to work and function as desired for all groups. Details about construction or mechatronic properties of the engine are presented and discussed in detail in the separate reports [7], [8].

1.6 Project goal

The goal of this project is to produce a functioning prototype of the GREC as proof of concept. This is to be determined mainly by achieving a measurable pressure difference from the prototype. The contribution of this thesis is mainly focusing on the material properties, heating and fluid dynamics for the engine. Another goal is to investigate how energy can be recovered in the GREC.

1.6.1 Research questions

- What is the most optimal piston dimensions for the prototype GREC?
- How does the prototype differ in performance from the theoretical engine?
- How does different temperatures affect the performance of the prototype engine?
- How does different rotor speeds affect the performance of the prototype engine?

1.7 Long term goals

One of the long term goals of GREC is to reduce the use of fossil fuel by transforming temperature gradients in fluids, such as air, into mechanical work and be an alternative and green energy source. The plan is to stack multiple GRECs on top of each other to increase displacement and generate more energy. Reduction of waste heat emissions from industrial processes will be achieved with the implementation of the improved

GREC technology.

The long term goals resulting from the current project mostly revolve around improving the prototype. By improving the prototype it can hopefully become efficient enough to be implemented in factories for real. Increasing the efficiency is the most challenging and integral part in making the GREC a reliable method for reduction of waste heat.

1.8 Assumptions and limitations

The budget of this project limits the material selection and the overall design and size of the engine. As the engine will be built in reality the material and the design have to be able to be constructed easily. This may have an negative impact on for example the thermal properties of materials. Another limitation is that this prototype should be a small engine which results in that the goal is to achieve some pressure difference and not gain energy from the engine.

When calculating the piston dimensions, simulations from previous work is used to get a approximate dimension of the piston that can be used. In these calculations the processes of the cycle are seen as ideal, as the cycle of the engine is not known in reality.

1.9 Ethical view

From an ethical standpoint the GREC engine will generally be used to reduce waste heat in the industries and thus reduce their climate impact. The technique does not have intentions of being used in military applications that could create ethical problems. However since the technology only is in an early stage of development it could be used in other areas that could create ethical dilemmas. Furthermore the technology does not come with any sufficient dangers that could be discussed with an ethical standpoint.

2. Theory/Background

This chapter discusses the background theory behind the design and tests for the prototype engine. The theory mainly revolves around the thermodynamics implemented into the GREC engine and their respective equations. Basic mechanics and function regarding the energy recovery is also presented.

2.1 Heat transfer

Heat can be transferred in three different ways: conduction, convection and radiation. The relevant forms of heat transfer for this project is conduction and convection and will therefore be described in this section. [9]

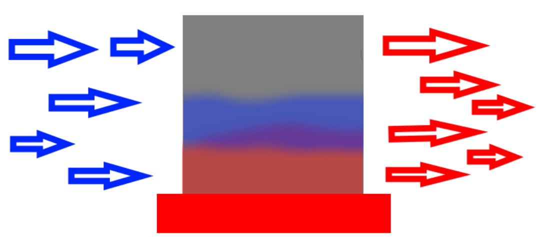

Figure 3: Visualization of thermal conductivity and convection. Heat is conducted inside the material while convection occurs between the solid body and the fluid.

2.1.1 Conduction

When two solid cylinder materials are in contact with each other, heat is transferred with conduction, see figure 3. The conduction heat transfer is dependent of the area, temperature difference and the conductivity coefficient which is a material property. A higher thermal conductivity results in more heat transfer and a low thermal conductivity means the material is a better thermal insulator. The thermal conductivity can be determined experimentally by heating a test piece and thereafter measure the heat rate. [9]

2.1.2 Convection

Another form of heat transfer is convection which occurs when energy transfers between a fluid and a solid cylinder body, see figure 3. Convection is conduction in combination with fluid motion where the fluid motion amplifies the heat transfer. Convection can occur either forced or natural. Natural convection is when the fluid motion occurs because of heated fluid rises and is replaced by cooler fluid. Forced convection occurs when the fluid motion is forced, for example by a fan. The heat transfer rate is increasing with higher speed of fluid motion. Turbulent fluid motion will also increase the heat transfer. [9]

2.2 Equations

Under this section the equation used in this project will be presented and referred to when used in the report. To calculate the moving boundary work of a expansion/compression the following equation is being used.

$$W = \int_1^2 P dv \tag{1}$$

Polytropic processes can be described with the following two equations where n is the polytropic exponent which differs between different processes.

$$PV^n = C \tag{2}$$

$$P_1 V_1^n = P_2 V_2^n \tag{3}$$

For a general polytropic process the work can be calculated with the following equation where n is the polytropic exponent.

$$W = \frac{p_2V_2 - p_1V_1}{1-n} \tag{4}$$

For an isothermal expansion/compression n is equal to one and the work can be described with this equation.

$$W = p_1V_1 ln(\frac{V_1}{V_2}) \tag{5}$$

The power can be calculated with this equation where v is the rotation speed in RPM and W is the work.

$$\dot{W} = \frac{W * v * \pi}{60} \tag{6}$$

2.3 Thermodynamics

In this section the thermodynamics of the GREC is presented both with a theoretical view and what the differences will be in practice.

In thermodynamics a process is defined as a change of state in a system in which the change in the system refers to a change from an initial state to an equilibrium state. A theoretical limitation is to consider quasi-static processes which happens when the change of state is occurring slowly so that the system is in the same internal equilibrium. An example of this is an isothermal process where the temperature of the system remains constant. This will be more thoroughly described under Carnot cycle. [9]

As described previously, the GREC is working as a heat engine by rotating a WGV between a warm and a cold side. Expansion and compression of gases can be described as a polytropic process that follows the equation (2) where P is the pressure, V is the volume, n is the polytropic exponent and C is a constant. Different values on the exponent n is used to describe different special cases of polytropic processes. Examples of these special cases is an isobaric process where n=0, an isothermal process where n=1 and an isotropic process where n=k, k=1.4 for air in room temperature. A process can not in reality follow one of these processes due to losses and irreversibilities. They can however be used as assumptions to describe and calculate a theoretical process and value close to the real results. [9]

2.3.1 Carnot cycle

To theoretically describe the GREC cycle some assumptions and simplifications has to be done. Traditionally the Carnot cycle is used to describe the processes of heat engines. Even though the GREC is not identical to the classical Carnot heat engine it resembles it well because of a gas creating mechanical work out of a hot and cold reservoir.

When the WGV is rotated to the hot side it gets heated and the pressure rises. This causes a volume expansion that pushes an external piston, creating work. During the expansion of the WGV the pressure is dropping. Due to the fact that the volume is in contact with a hot reservoir the temperature during expansion will remain the same. The expansion can in theory be described as an isothermal expansion. After the expansion the WGV is only in contact with the insulating fin resulting in more expansion but with no heat added. This relates to an adiabatic expansion which is another step in the Carnot cycle. Similarly when the WGV is rotated to the cold side, the temperature and pressure will decrease forcing a compression which pushes down an external piston. If the volume in compression is in contact with a cold reservoir the temperature will remain the same and the compression can be seen as isothermal. After the compression the WGV is rotated to the other insulating fin resulting in more compression. However, since its over the insulating fin no heat will be transferred and thus this step of the cycle is considered an adiabatic compression. These processes resembles the processes of a Carnot cycle well however it is not possible due to losses that will be described in more detail. [9]

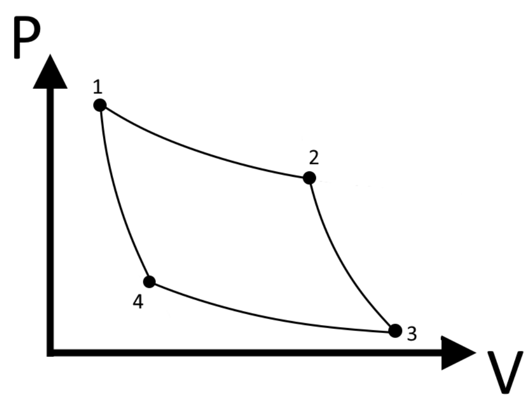

Figure 4: P-V diagram of an ideal Carnot cycle.

2.3.2 Losses

In the theory above all thermodynamic processes is considered reversible. A reversible process is when the process can be reversed back to the original state, meaning that the cycle can work in the opposite direction. This is impossible in practice because of losses that make the cycle irreversible. One irreversibility is friction which is occurring when either two solid cylinder bodies are in contact or a fluid is in contact with a solid cylinder body. In the GREC engine it will be little to no friction between the RS and the fins, however there will be friction between the WGV and the RS. This will create heat and this heat can not be reversed back to mechanical energy. The friction is therefore considered a irreversibility. Another irreversibility is heat transfer through a finite temperature difference. When a heat transfer has taken place it can not be restored to its original state without adding work. For example, if a cold body is heated by a warmer surrounding it is impossible to restore the cold original temperature without adding work. The body will be restored to its temperature but the surroundings will not since heat will be taken from it. This makes the process is irreversible. It is thermodynamically impossible to remove the irreversibilities completely but reducing them as much as possible will enhance the efficiency of the engine. This is the reason for the importance of minimizing friction and maximizing the heat transfer, and thus minimizing the irreversibilities of the engine cycle. [9]

2.4 Fluid mechanics

Fluid motion can either be laminar or turbulent which is dependent of velocity, face toughness and face temperature. Turbulence is defined by chaotic changes in velocity and pressure unlike laminar flow which is characterized by flow in ordered layers. Turbulence can be determined with the Reynolds number which is the ratio of inertial forces and viscous forces. Turbulence will occur when a critical Reynolds number is reached. With fluid motion along a flat plate the critical Reynolds number is $5 \times 10 \wedge 5$. With turbulence heat transfer between the fluid and a solid cylinder increases. [9] It is noted that theoretically the heat transfer in the GREC increases with a more turbulent flow [5].

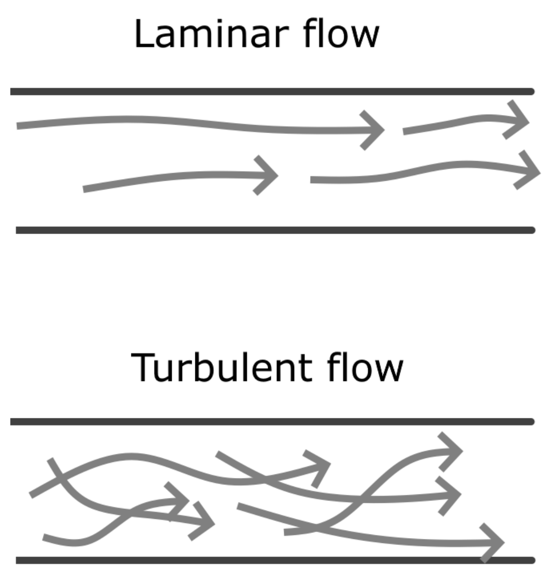

Figure 5: Illustration of laminar and turbulent flow in a tube.

2.5 Energy recovery

The purpose of the engine is to generate mechanical energy from a difference in temperature inside the engine. This can be done with different methods. The main energy recovery mechanism discussed in this project is a piston. This section presents theory about how pistons function and how they can be used to convert heat into mechanical energy.

2.5.1 Piston function

Piston engines are primarily made up by two components, a disc and a cylinder. The disc is enclosed inside the cylinder and moves when the fluid inside expands and contracts. Fluctuation in volume is directly connected to heat and pressure fluctuation. This makes pistons ideal for transferring heat energy into mechanical work. Therefore pistons are often used as a component in heat engines[10].

The disc moves when the difference in heat and pressure between the two sides becomes larger, see figure 6. In short the disc moves up when the heat and pressure in volume 1 is larger than in volume 2. Volume 1 and 2 representing one side of the disc each. Similarly the disc retracts back from it's end position when the heat and pressure in volume 1 is less than in volume 2. The disc is often connected to crankshaft or a similar component. The linear movement of the pistons results in a rotating motion of the crankshaft. This rotation can thereafter be used to power a machine or store energy in a flywheel [10].

Several parameters are important in order for the piston to work efficiently. Heat fluctuation has to occur in order for the disc to move. The size of the cylinder is directly dependent on the achieved heat fluctuation. Considering that the work output also is dependent on the size of the piston it's often desired to have high heat fluctuation. Larger piston sizes generate a larger friction force inside of the cylinder. This makes the requirements for high heat fluctuation more demanding.

The area between the disc and cylinder walls has to be sealed. If leakage occurs between the two sides of the disc the piston will become less efficient. If enough leakage occurs the piston won't work at all since the heat and pressure difference between the two sides will be minimal. Since friction force decreases the efficiency of the piston this has to be considered when sealing. O-rings with lubrication or piston rings are therefore often used as a sealing method inside the cylinder depending on application. Sealing and lubrication are therefore key factors when optimizing the piston size.

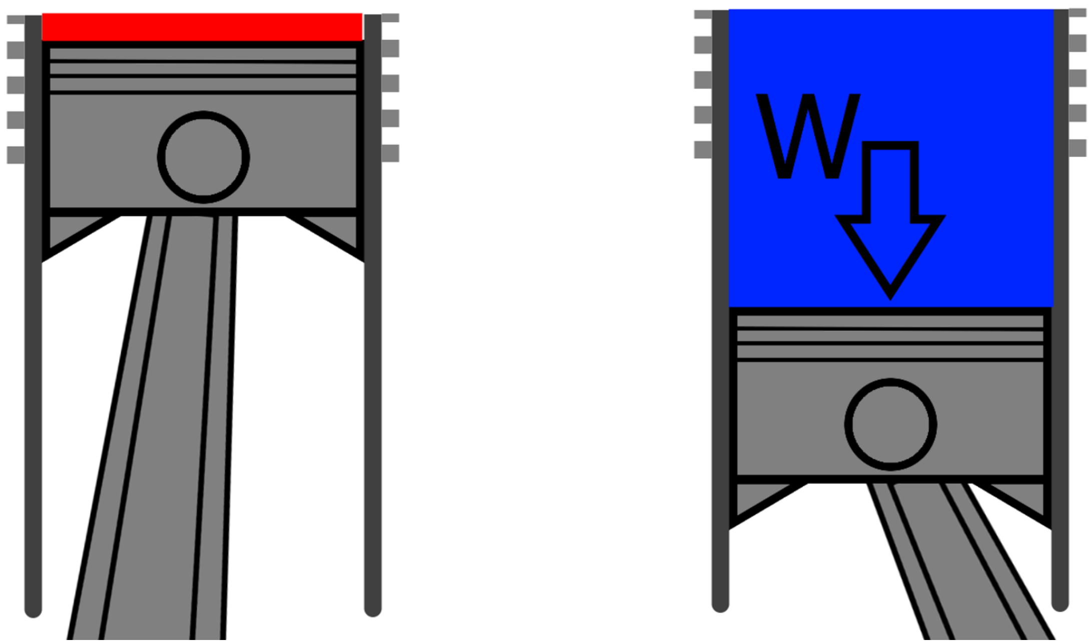

Figure 6: Simplified 2-stroke cycle. Compressed fluid in a closed volume with high pressure and temperature on the left. When the fluid expands it presses on the piston with a force and generates mechanical work.

2.5.2 Void volume

Void volume refers to a part of a total volume that does not contribute to the system performance. In this case not contributing means that the void volume isn't receiving any of the energy input that the rest of the volume does. The void volume is still connected to the total volume and is still involved in the work produced by the system. The void volume is however called "void" since that specific section of the volume doesn't add to the performance. Instead it decreases the efficiency of the system. Reduction of the void volume is important, especially for a system that makes use of volume and pressure to produce work and power.

2.5.3 Compression ratio

The compression ratio in a piston engine is the ratio between the biggest achievable volume and the smallest. The volume when the piston is at it's lowest position is often referred to as bottom dead centre, or BDC, and the volume when the piston reaches its highest position top dead centre or TDC. The compression ratio is simply calculated by dividing the volume at BDC with the volume at TDC. [11] In a closed system the thermal efficiency and output power is directly proportional to the compression ratio.

In modern Otto engines the compression ratio usually lies between 9:1 and 12:1, and between 18:1 and 23:1 in Diesel engines, which is why they generally are more efficient. Theoretical heat engines work using the same principle. In a Carnot engine, and therefor the GREC engine, a high compression ratio is desirable. Worth mentioning is that for a high compression ratio to be efficient the system also has a expansion ratio same as the compression ratio. This is because the compressed fluid has to be able to expand as much as it is compressed, otherwise the energy stored will be insufficient to move the piston all the way to BDC and complete the cycle.

2.5.4 Calculations of work

When gas expands and compresses to move a move a piston it is considered a closed system. The boundaries of the closed system is in between the cylinder and the WGV, meaning that the WGV is not considered in the equations for the boundary work. The work done to move the piston is called moving boundary work because of the change of volume during the expansion and compression. The boundary work can be calculated as the area under the curve in a P-V-diagram and can therefore be evaluated by integration leading to the equation (1). [12]

The solution to the integral (1) is different for different processes but for the general polytropic process the equation for the boundary work is **??**. [12]

If the GREC cycle is considered to work closely to the Carnot cycle the polytropic exponent n is equal to one. Solving the integral and adding the ideal gas law $PV = nRT$ results in the following equation for the moving boundary work (5) [12]

However this is assuming that the GREC engine in reality is following the Carnot cycle which is impossible in practice, as described above. [9]

3. Method

This chapter presents the implementation of the background theory and how the work was carried out. In deep discussions about how things work fundamentally is not presented in this chapter, but rather how the prototype was conceived. The method of which the resulting piston volume is calculated is also presented.

3.1 Material testing

The workshop handed us an unknown material, supposedly similar to bakelite. This is of interest since bakelite was found to be a usable material for several components in previous reports [5]. After discussion and investigation the material was determined to be some sort of fiber reinforced plastic (FRP). To investigate if the material is suitable for the RS and the insulating fins, the thermal conductivity was tested experimentally. To test the thermal conductivity a test rig was used, see figure 7. The test piece was placed and compressed in the machine and then heated on one side and cooled on the other side. With the thickness, pressure and temperature being known the machine could compute a value for the thermal conductivity. It is also relevant to determine the density of the material to know if it is suitable for the RS. The density was calculated by weighing a test piece and measuring the volume and dividing the weight by the volume.

The heat transfer of both the conducting fins and insulating fins was done to physically test the heat transfer of the conducting and insulating materials. The conducting material was tested by heating the material with a hot plate. The temperature gradient was measured with a thermal camera to see the spread of heat in the material. The same studies for the insulating material was done by placing a piece of insulating material on a piece of heated conducting material. Thereafter the heat spread of the insulating material was measured with a thermal camera.

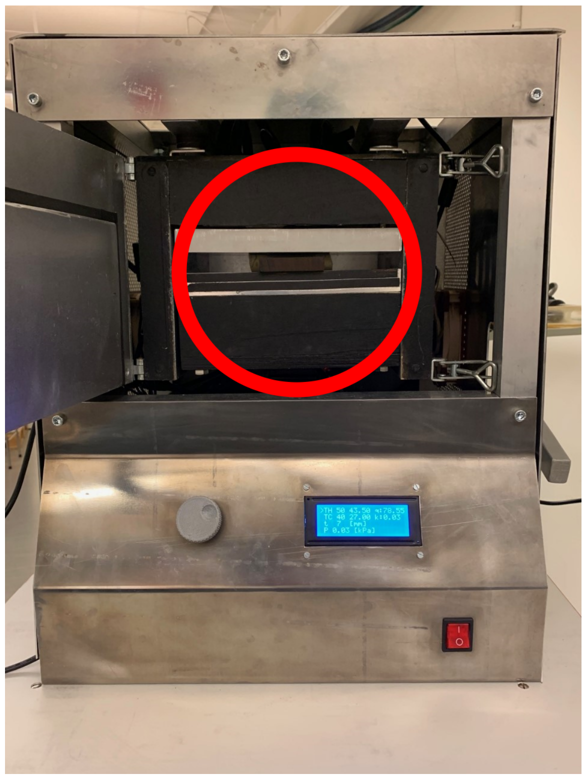

Figure 7: HTC-testing setup, the red circle highlights the material specimen and its placement for the test.

3.2 Material selection

The material selection of the GREC engine is essential for it to be as efficient as possible. As described in the section "Technology behind GREC" the most important parts of the engine when regarding heat properties is the RS, conducting fins, insulating fins and the shell. Table 2 shows the resulting material parameter values from the material tests.

Table 2: Material Properties for the used materials, EN AW-5083 plancast is a cast aluminium alloy and FRP is a fiber reinforced plastic. The k-value refers to the thermal conductivity coefficient.

Material	**Density** [kg/m^3]	**k-value** [W/mK]	**Young's Modulus [GPa]**
EN AW-5083 plancast	2600	117	71
FRP	1550	0,8	50

3.2.1 Revolving shutter

The purpose of the RS in the GREC engine is to rotate the WGV around and move it between the heating and cooling fins as well as the insulating fins, see figure 8. To be able to rotate with a high velocity it requires the material to be stiff enough to ensure that it doesn't elastically deform and cause friction against the fins. Another important property for the RS is the thermal properties. To achieve a functioning and efficient GREC engine there should be as little heat transfer from the heating fins to the RS as possible. Otherwise the heat will transfer from the hot fin to the RS and onwards to the cold side. This in turn will increase the temperature of the cold fin and decrease the temperature gradient. Consequently the material for the RS should be relatively insulating and thus have a low thermal conductivity, k. Due to tight tolerances between the RS and the fins it is desired to have a material with low thermal expansion to reduce the risk of friction between the moving and stationary parts.

Fiber reinforced plastic was chosen as the material for the RS for several reasons. The material is lightweight and stiff as can be seen in table 2. This is mandatory since the RS experiences large centrifugal forces due to the fast rotation. The material being lightweight is important because it lessens the load for the electrical engine. Lastly the material has low thermal conductivity which is desired for the RS. All these factors

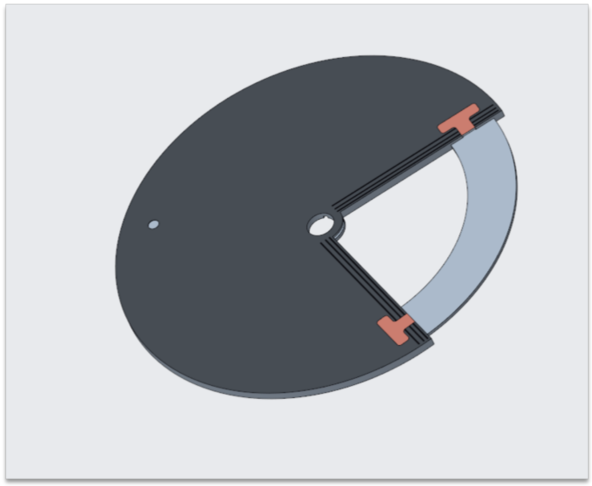

Figure 8: An illustration over the design over the RS.

combined with the ease of access made the FRP the most suitable material choice for the RS.

3.2.2 Conducting fins

The main point of the heating fins is to transfer as much heat as possible from an external heating source to the WGV. Therefore the heating fins have to have high thermal conductivity and high specified heat capacity to maximize the heat transfer rate. For the cooling fins the same principles applies, a high thermal conductivity and heat capacity results in a high cooling rate between the WGV and the fins. Furthermore it is desired to have a low coefficient of thermal expansion because if the material expands during heating it could create friction between the heating fin and the RS. The conducting fins can be seen in figure 9.

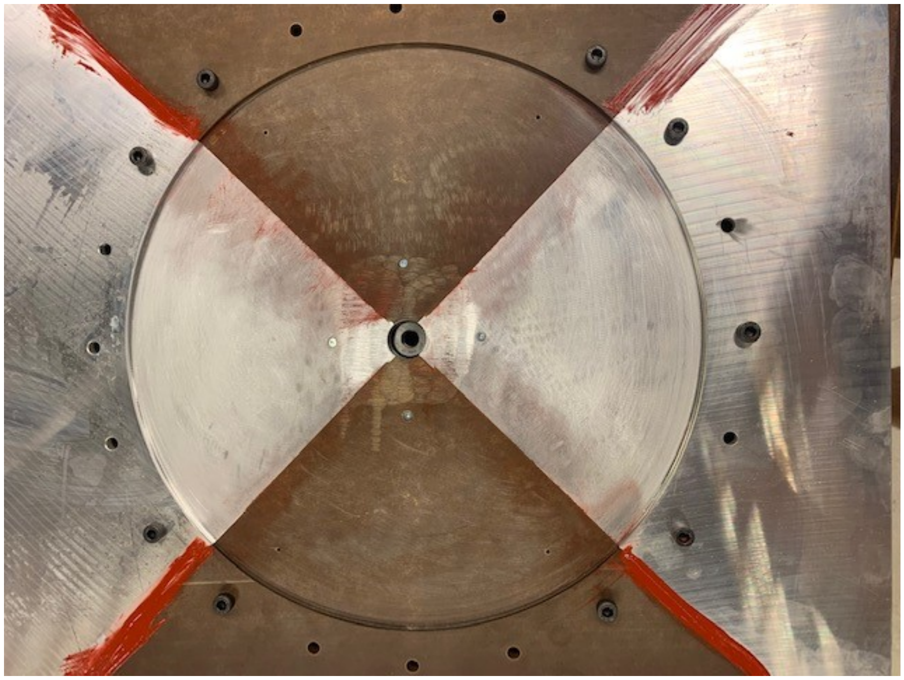

Figure 9: Image of the conducting and heating fins of the GREC. The brown fins are the insulating fins made of FRP and the aluminium fins are the conducting fins.

Cast aluminium was chosen as the material for the conducting fins. The reasons for why aluminium is a suitable material is because it has great thermal material properties. The material has high values for both thermal conductivity and heat capacity, see table 2. These properties allows for wide heat spread in the fin and for high heat transfer from the heating source. Copper was also a great material choice for the fins, having even greater thermal properties. This was discussed in the first report made at Linköping University [5]. Copper is however much more expensive than Aluminium and is therefore not a suitable material choice in this experiment. Aluminium is also the preferred choice over copper when looking at constructional, tolerance and strength properties, for details read the construction report [7].

3.2.3 Insulating fins

Opposite to the conducting fins the insulating fins should exchange as little heat with rest of the engine parts as possible. Mainly this is because the fins are required to isolate the heat transfer between the hot and cold fins. The insulating fins will get heat applied via conduction from the heating and cooling fins. They will also get heat transfer via convection from the WGV. Accordingly the insulating fins must be made of a material with low thermal conductivity to minimize its heat exchange with the conducting fins and the WGV. The insulating fins can be seen in figure 9.

The chosen material for the insulating fins is fiber reinforced plastic. The material has low thermal conducitvity and is also stiff enough to be one of the foundational components. FRP can also be processed to have low tolerances which is required for the RS not to touch the fins during rotation.

3.2.4 Shell

The shell is not as essential as the other parts for the heating function of the engine. A relatively insulating material is optimal to minimize unnecessary heat exchange in and around the engine. The shell shouldn't transfer heat between the hot and cold fins. Many of the engine's sensors are placed on the shell which means that the shell must stay at low temperatures even when heat is applied. Otherwise the sensors will melt which is undesired. Fiber reinforced plastic was chosen as the material for the Shell since it has all the desired properties. The material is also easy to access since it already is used for many engine components.

3.3 Heating source method

Hot plates were chosen to be the heating solution for the heating fins. There are several reasons why hot plates are desirable for this specific setup, mainly budget constraints and simplicity. Other options considered such as induction were either deemed too expensive as an option or too extensive when regarding setup and design. The previous heating source method made use of tea lights to heat the heating fins. This method was deemed flawed since it is inconsistent and doesn't allow for proper heating regulation. Heating regulation is desirable for safety reasons as well as allowing for wide testing variation.

Since conceptualisation for the heating source method had to be completed before the engine design was finished older engine parts from version 2 were used. The reason for this is that the engine and the heating fins were designed with the heating source method in mind. Since the previous heating fin had roughly the same dimensions and shape as the new design tests with the hot plates were carried out. The results found when heating the old heating fin with one hot plate showed a maximum heat achieved of 230 degrees Celsius. The peak temperature occurred near the outer parts of the fin. The air flows the fastest along the outer part of the WGV which allows for a higher degree of heat transfer in that region. This in turn allows for a larger increase in pressure which in theory allows for more work to be produced by the engine. Considering all these factors and results we can conclude that the heating solution is satisfactory for the chosen design when regarding heat transfer.

The setup for the final design makes use of the same type of setup as tested before. It consists of two hot plates, one for each side of the heating fin. The hot plates are produced and sold by Biltema AB and have a power output of 1500W each. They also have heating protection and heating regulation which were criteria we had for the products. This was for safety and test variety reasons. The reason two hot plates are used is because this allows both sides of the heating fins to be heated equally. This also provides application of heat transfer to the most crucial parts of the fin, the center and outer parts of the WGV. Heat is also applied to both sides of the fin which allows for greater heat distribution in the fin while also allowing for a higher peak temperature in the crucial areas. The final setup can be seen in figure 10. The setup makes use of conduction between the hot plates and the heating fin.

Figure 10: The heating source method setup consisting of two hot plates, one on each side of the heating fin.

3.4 Cooling method

The cooling method for the cooling fin is not of the same importance as the heating source method. This is because the realistic achieved cooling temperature is substantially lower than the potential heating temperature. The main reason for this is that it's easier to implement satisfactory heating source methods than cooling methods.

The main purpose of the cooling solution is not to cool the fin to sub zero temperatures, but rather to keep it from heating up. The fins will heat up when the WGV and hot air passes from the heating fins to the cooling fins. A cooling fluid temperature between 0 and 10 degrees celsius was therefore deemed satisfactory.

The chosen cooling solution is to make use of cold water in a tub. The water cools the fin by absorbing the heat from the fin through convection. Methods using air as cooling fluid or other types of processes where also considered. Implementations of sufficient cooling methods for air are however much more complicated and expensive to implement than the chosen solution. Since the GREC is standing vertically with the fin in the tub most of the fin is connected to the water. Considering that the criteria for the cooling method are quite low the chosen method was deemed as satisfactory.

3.5 Sensor placement

The sensors and their placement is the main focus for conducting the experiments on the finished engine prototype. The placement is crucial in order to properly analyse if the theory behind the engine is realistic and achievable with the current design. Pressure and position sensors are used to measure the performance and efficiency of the engine and its implemented design ideas. Temperature sensors could not be implemented due to mechatronical and construction problems, for further details regarding these areas read the separate reports [7], [8].

3.5.1 Pressure sensors

The placement of the pressure sensors is the most important part of the sensor placement in general. This is because all other data accumulated by the position sensors is irrelevant without pressure data. Since the pressure sensors are the most important these were crucial to place properly. The placement of the sensors should provide minimum leakage and be placed in order to measure the most important and interesting data. By this we mean that the sensors are placed so that they measure the peak pressure in the engine. This is because the main focus of the project is to achieve a measurable pressure difference inside the WGV.

The engine makes use of five pressure sensors. Four sensors are placed so that they are connected to the WGV. This in order to measure to pressure fluctuation near the conducting fins when the RS rotates the WGV. One sensor is placed inside the void cylinder of the engine to measure the pressure achieved near the piston entrance and exit. Whether the sensors measure at the entrance or exit of the imaginary piston, in this case the void cylinder depends on which void cylinder is used during the experiment. The purpose of the different void cylinders and their respective measuring points are discussed in detail in the energy recovery chapter.

As mentioned in the Background theory the fastest air flow speeds occur near the corners and outskirts of the WGV. This results in the flow being the mot turbulent in these areas and therefore the heat transfer also being the highest. In theory this should mean that the pressure achieved should peak there as well. It was therefore of importance to try and place sensors on the outskirts and corners of the WGV, either on the conducting fins or on the insulating fins.

The insulating fins were chosen to be the placement areas rather than the conducting fins. The reasons for this were mainly due to construction and heating criteria. The sensors would melt if placed on the heating fin since the fin reaches peak temperatures of over 250 degrees. Building the sensors into the conducting fin construction would also prove difficult from a construction standpoint. Mainly this is because the cast aluminum was chosen over cold worked aluminum for tolerance, heating and balancing reasons. Deformation by drilling or other forms of processing was deemed risky and unnecessary considering the material selection criteria. Further details regarding construction and material constraints can be seen in the construction report [7]. If the manufacturing would end up flawed or if the design wouldn't work for other reasons, reproduction of the fins wouldn't be possible due to budget constraints. All things considered the fins were deemed to be a poor choice to place the sensors.

The insulating fins were the better choice when considering several factors. The sensors can be placed in equal areas position wise, meaning that they could be placed near the outer radius of the WGV. Since the fins isolate heat the sensors won't experience high enough temperatures to melt och take damage.

The resulting design and placement can be seen in figure 11. Two sensors are placed over each insulating fin, one near each side where the insulating fins and conducting fins are connected. This is to make sure that the pressure is measured just after the WGV leaves the heating fin and just before it enters the cooling fin area. In theory this should make the pressure differences that occur due to heat change measurable. The pressure drop that occurs when the WGV is in the insulating fin area should also be measurable. With this data it should therefore be possible to properly analyse both the pressure ratio, the pressure leakage and indirectly the heat leakage of the engine.

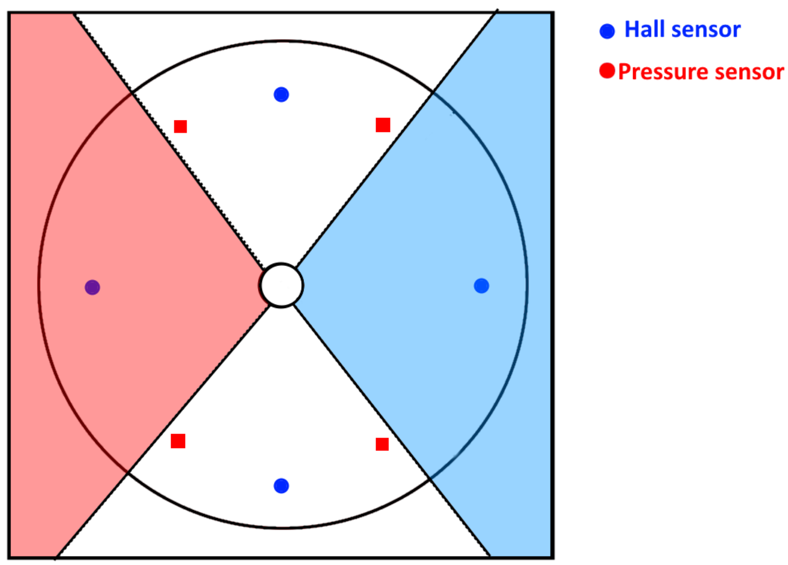

Figure 11: Visualisation of the sensor placement.

3.5.2 Position sensors

The position sensor arrangement consists of five components. Four position sensors measuring the magnetic field are placed on the shell, over the conducting fins and insulating fins. One is placed over the middle of each area as can be seen in figure 11. The magnet is placed on the RS on the opposite side of the WGV as per 12. The setup was chosen as such in order to allow for precise observation of the WGV's position. This combined with the pressure sensors allows for accurate measurements of the WGV pressure by its position. This data allows us to analyze how much leakage and reduction in pressure occurs when the WGV is in the isolation area. This is important data since this is something that is undesired and bad for the overall performance. We should also be able to analyze how much pressure increase and decrease occurs when the WGV is in the heating and cooling fin areas. All this data can then be used to find improvements when regarding construction and materials.

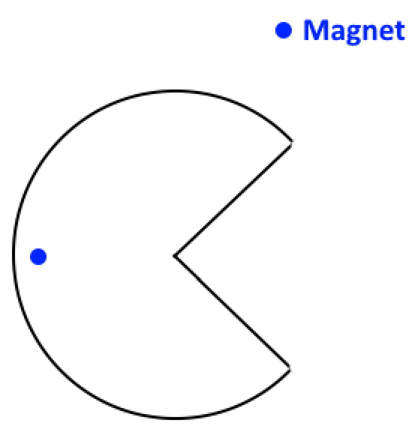

Figure 12: Magnet placement on the RS.

3.6 Revolving shutter sealing solution

The engine design presents several problems regarding friction and overall ability to keep the system sealed. The RS is the main component that creates these problems. The reason for this stems from the fact that the RS needs to have low friction in order to rotate at high speeds. This results in a design were a gap between the RS and the shell and fins is desired. However if this design was implemented the WGV would become much larger since it in reality would be the entire engine volume. This means that the dead volume for the WGV would become the entire engine instead of only the inside of the axle. Since a large gap can't be used and friction still must be minimized we came up with the implementation of slits into the RS design.

Slits have already been discussed and studied to a small degree in a previous report [5]. The slits in the report were however implemented and studied as infinitely thin lines which resulted in turbulent airflow occurring near them. By applying the theory for these slits in a realistic way, therefore not as infinitely thin lines we can achieve the same results. Meaning that we can create turbulent airflow on the edges of the RS. The design implements three slits on each side of the WGV on the RS, and on both sides of the disk itself. The resulting design can be seen in figure 13. The intention with the design is the reduction of leakage between the WGV and the rest of the engine volume. The slits create turbulent flow when air passes over them which then acts like a sealant between the WGV and the rest of the volume. Theoretically this results in a satisfactory sealing method and minimal friction since the RS is not in contact with the shell and fins.

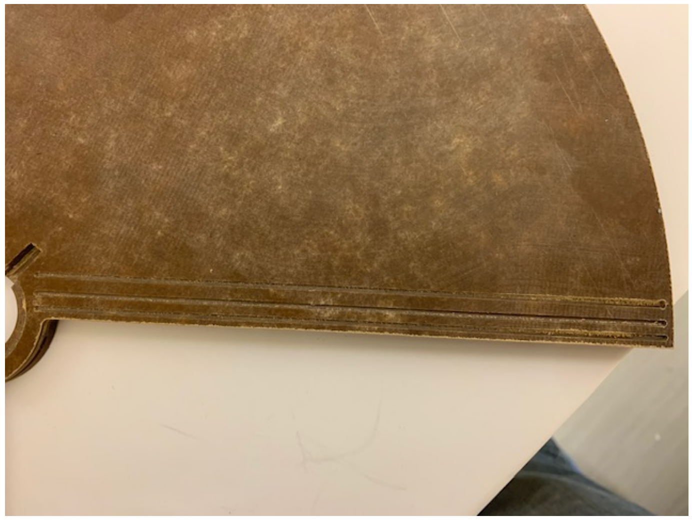

Figure 13: Slits on the rotating shutter. Three slits are placed on each side of the WGV and on both sides of the RS.

Three slits were decided as satisfactory since it should act as good enough of a sealant while not being too difficult to implement construction wise. The reason this can't be confirmed is because no simulations were carried out before construction began and calculations are complicated to do by hand. Theoretically however, the slits should be useful.

3.7 Piston/cylinder dimensioning

As mentioned above, the compression ratio should be set the same as the expansion ratio to ensure that the pressure is sufficient to move the piston and complete the stroke. In a normal piston engine this is elementary, since both ratios are equal and decided by the geometry. This does however not apply to the GREC engine since the piston is always connected to the WGV. The expansion and compression of the fluid, which in turn raises and lowers the pressure in the cylinder, determines the expansion ratio and therefor the total compression ratio. In earlier studies pressure differences of around 5kPa have been achieved. [5]

This is equivalent to an expansion ratio of around 1,05:1 Because of this the compression ratio will be relatively small in our case, since the WGV and void volume always is connected to the cylinder block. The total volume will not increase by a factor 10 like in a typical Otto engine, we are looking at total compression ratios in the range of 1,05:1 and 1,1:1.

Using the polytropic equation (2) we can set up the equation (3) where V_1 and V_2 refers to the BDC and TDC.

The process is seen as isothermal, which implies that n=1. By solving for V_2. the cylinder volume can thereafter be calculated.

The difference between V_2 and V_1 will be equal to the cylinder volume. This will be the change in volume required for the pressure to drop to 101,3 kPa, or 1 atm given that the process is ideal and isothermic. Since the compression ratio is 1,05 we therefore get a ratio for the volumes.

Using this method we calculated a cylinder volume and approximated two others with different volumes. The resulting cylinder volume was 24 CC. The three chosen cylinder volumes were 5, 10 and 20 CC. The reason for this is that the real process for the engine isn't as ideal as the calculated engine and the achieved pressure difference is likely lower. Therefore smaller void cylinders were created for testing variation.

To be able to test the real efficiency of the engine all three void cylinders were tested individually. They were placed on top of the engine, instead of the cylinder block with a piston, and contain a pressure sensor each. Running the engine with these three constant volumes simulates a piston moving up and down. The desired result is a high pressure with the small volume and a low pressure with the large volume. If the pressure drop is too small when the larger volume is fitted we automatically know that we can use a larger volume, which will generate more power.

The dimensions for the void cylinders only vary in height. The inner radius was set to be the same as the inner radius for the axle. The reason for this is that the void cylinders shouldn't have a wider inner radius because this would create flow losses in the void cylinder.

3.8 Engine tests

The testing of the engine was started by heating up the hot side to the maximum temperature from the hot plates and cooling down the cold side with the cooling method presented above. After that the electric motor was started and set to spin at a constant rotational speed of 150 rpm. The three different void cylinders presented earlier were prepared to be mounted on the engine to simulate different positions of a piston. Starting with the smallest cylinder, the tests begun.

Using these measured pressure values the work and power can be calculated with the equations presented earlier in the report. Different temperatures of the hot side can be used to see the difference in performance of the engine with different temperatures. Values from the four pressure sensors on the shell was saved and mapped to their corresponding RS position, RPM etc.
To calculate the work generated from the GREC the integral (1) is solved by assuming the points in pressure builds a linear function in a P-V-diagram, see figure 14. The area under under this function is consequently the work out put from the expansion and the compression of the WGV. The total work generated for one rotation of the GREC is the work from the expansion in addition to the compression. The power of the engine is calculated by multiplying the work for one rotation by the angular velocity using the equation (6).

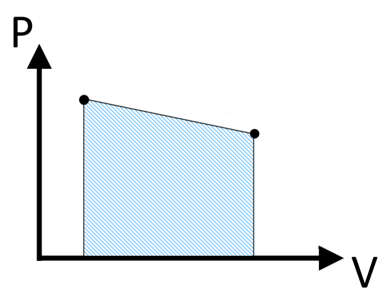

Figure 14: A schematic figure over a P-V diagram where the work is the area under the function. The figure is only for an expansion of the WGV and the same principal applies for the compression.

4. Results

In this section, the results for the engine tests and calculations are presented. Chosen materials and heating/cooling methods are not seen as results and are presented in the method chapter.

4.1 Engine tests

The result of the engine tests are showed in figure 15 . The rotation speed during the test was set to 150 RPM and the temperature on the hot side was set to maximum which resulted in a temperature around 250 degrees at maximum, see section material testing. Since the result showed no pressure difference (see discussion), the work and power can not be calculated.

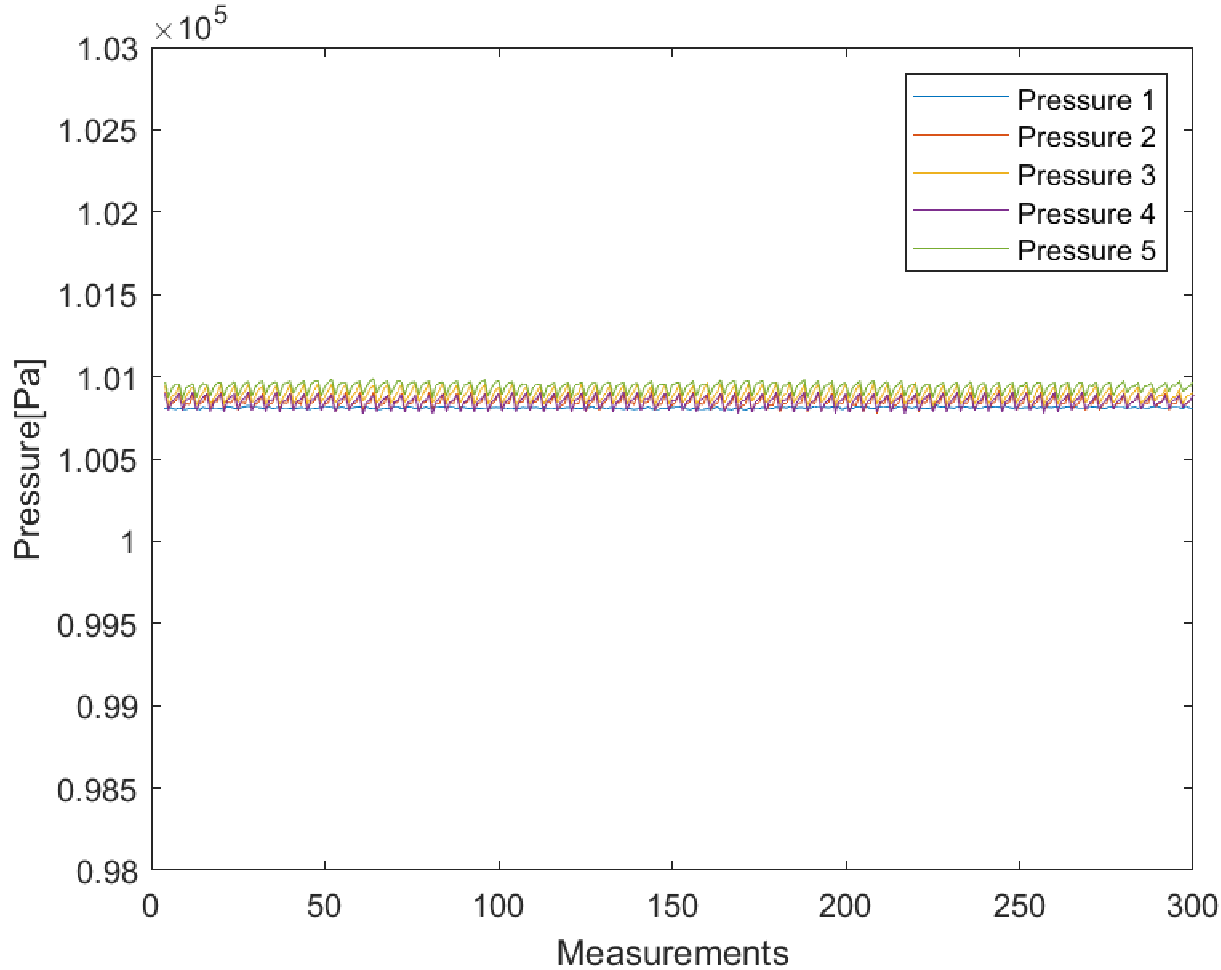

Figure 15: A graph over the pressure from the different pressure sensors which is presented under method. The x-axis is the measurements, i.e the testing was done with 300 measurements per sensor. The y-axis is the measured pressure from the sensors.

5. Discussion

This chapter presents discussion regarding the methods conducted during the project and discussion regarding the results.

5.1 Method discussion

The timeframe for the entire project resulted in limitations regarding conceptualisation and design of the engine. This meant that much of the foundation for the engine was taken from previous reports and studies. Simulations and calculations for different heating source methods, rotation speeds and materials could possibly have resulted in different designs and methods. This was not possible to do in time however due to the time constraints.

The main advantages by making much use of the previous work is that the resulting engine in many ways is a directly developed from all the previous work. Much of the different studies done for the engine have been used in some way in this project. The slits that were studied to create turbulent flow in the WGV have now instead been used on the RS. The previous work has therefore been adapted as much as possible to create the most optimal engine. Not everything could be used however. The work surrounding heating source methods for the heating fin made use of techniques that were difficult to implement due to budget constraints. It can however maybe be used in future models to create a more optimal engine.

The main disadvantage with using much of the previous work and not redoing much of it ourselves is that we didn't know how the final design would function. Much of the conceptualisation became reliant on the previous work and we had to guess how well it would work for our design. The design could therefore be less optimal than it could have been with more background work before the implementations. The conceptualisation process for each component and material was however studied and discussed to reach the most optimal result possible.

Temperature sensors could not be used for the prototype since they couldn't be implemented in a desired way. The reason temperature sensors would be useful is that it would allow for analysis of the engine leakage. It would also allow us to see how much the heat spreads from the hot fin to the cold fin. The data would help in material selection and design ideas for future work since heat spread between parts is unsatisfactory if it occurs. It would also help in evaluating our material choices. Therefore temperature sensor implementation something that should be studies in the future.

The purpose of the different void cylinders was to simulate different cylinder volumes. This in order to decide to proper piston size for the final GREC design and size. The smallest void cylinder represents a piston in its lowest position. The bigger void cylinders represent the piston in its end position. The different sizes for the bigger void cylinders decide the size of the piston. In theory, the void cylinder that achieves normal air pressure at it's endpoint would determine the piston size. Compression ratio is mainly the reason for this. The optimal piston size should achieve high pressure at its low position when the WGV is heated. The disk would then move towards the end position at which the pressure should be normal air pressure when the WGV is cooled down. A change in pressure in any direction either means that the engine is less efficient.

The void cylinders do not act the same way as a piston would though. The volumes one and two inside the piston changes when the disk moves for a real piston. Therefore only one piston size is used, only the volumes one and two inside the cylinder change.

To simulate the achievable volume change inside a imaginary cylinder, different void cylinders were used. The void cylinders had to be tested individually and then be switched between tests. This resulted in different processes and conditions for each respective void cylinder. If a real piston was used there would only be one process and starting condition. The different starting conditions and processes result in that the achieved pressures in each void cylinder are different than what they would be for a piston. The choice of piston size is therefore something that needs to be reevaluated.

The movements of the cylinder is not either represented with these tests. This is because the disk adds friction which reduces the achievable piston size for the engine. This is not represented by the tests.

The different void cylinders were mainly used to figure out the size range for pistons and to approximate a piston size. We think that the results were satisfactory in this regard. The results were however far from perfect and can't be completely trusted. The void cylinders do not perfectly represent different piston sizes and the results are not completely accurate.

In conclusion, the only way to find the optimal piston size is to actually try different piston sizes on the engine in reality. This could not be done in this project due to budget and time constraints. The results found in this study can hopefully be of use to find the range of piston sizes for future testing.

5.2 Result discussion

As the result showed in the figure 15 the pressure difference is not measurable in any of the five sensors. Since the temperature distribution was very good on the outside of the engine the temperature of the engine was not the problem regarding the lack of pressure difference. The main reason to the result was probably leakage which was one of our risks for bad performance. It is hard to know exactly where leakage occurs in the engine but since the RS was rotating and it was a big temperature difference between the hot and cold side the only reasonable explanation for the results is leakage somewhere in the engine. Since we had some problems with friction we did not test the engine in any higher rotational speed but since 150 RPM did not show any results, a higher speed would most likely not be any better.

The heating source was functioning well since it heated the hot side to around 250 degrees. The design with the isolating fins also worked out well because of a low temperature in the cooling fin even after running the heating source and engine for a relative long time.

The cylinder dimensions were calculated using some approximations. The process was for instance seen as isothermal when calculations were carried out. Since the results did not show a pressure difference it is not possible to work out the optimal piston dimensions for the GREC prototype. With the same reasoning the thermodynamic process can not be determined since we do not have any pressure difference to calculate the polytropic exponent n.

There are several reasons for why the achieved pressure inside the engine may be lower than previously assumed. The engine pressure was approximated using previous work and simulation results. Even if the engine size was similar and our design has been designed to be as ideal as possible. In reality the engine may however be close to being ideal or far from it. Therefore the pressure was much lower than in theory and aswell so low so it was only measurement noise from the sensors.

Since the pressure difference was non existing future work regarding the prototype should be to see where the engine is leaking and try to fix this leakage. When this is solved more work with piston dimensioning and energy conversion can be carried out.

Aluminium has a melting point of over 600 degrees which is double the temperature achieved by our heating source method. Considering that a higher temperature results in higher engine pressure it would be of interest to study different heating source methods. Previous studies have made use of canals in the heating fins which could allow for better heat spread in the fin. There are also other possibilities like induction which couldn't be tested due to budget constraints that also could be of interest. This could be one of the focus points in future work for the GREC.

6. Conclusions

The main conclusion regarding the engine performance is that no pressure difference could be measured probably because of leakage.

With no pressure difference no conclusion regarding piston dimensions can be drawn and compared to the 20 CC that have been calculated with simulated data from earlier work.

The materials selected are satisfactory when regarding heat transfer and mech heat factors. Each component and material performs as desired during material testing. The heating source method is satisfactory since it allows for the heating fin to reach temperatures around 250 degrees Celsius and above. The materials performed well in the engine testing as well.

The next step in the development of the GREC is to seal the prototype from the leakage that is occurring right now. After that the next step is to implement a real piston for the engine and test how well it works for real. Implementation of a heating source method that allows for even higher peak temperatures as well a satisfying cooling method are also something of interest to investigate.

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