Design and assembly of a throttle for an HCCI engine

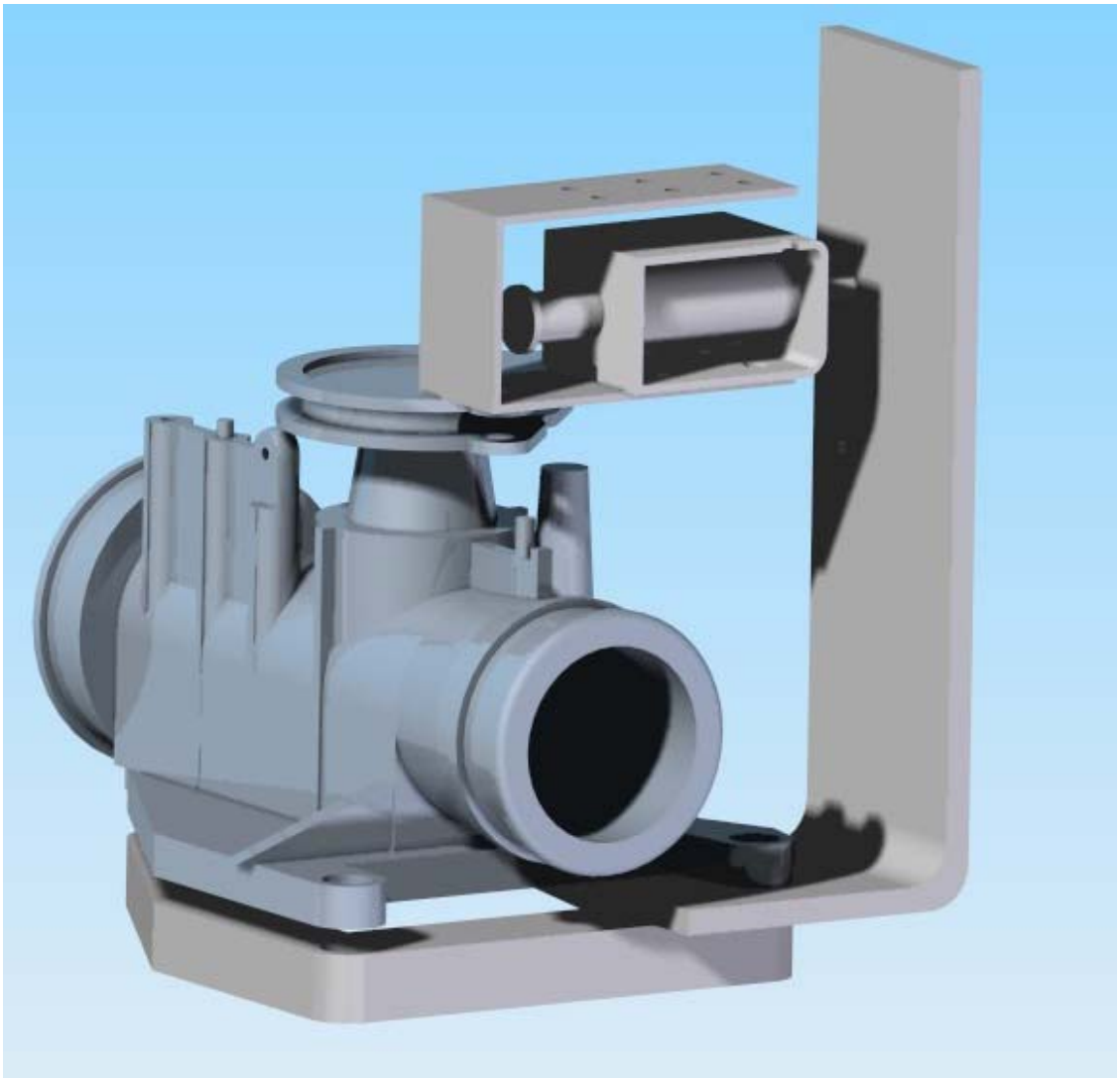
ÀLEX POYO MUÑOZ

KTH Industrial Engineering
and Management

Master of Science Thesis
Stockholm, Sweden 2009

Design and assembly of a throttle for an HCCI engine

Àlex Poyo Muñoz



Master of Science Thesis MMK 2009:63 MFM129
KTH Industrial Engineering and Management
Machine Design
SE-100 44 STOCKHOLM

KTH Industriell teknik och management

Examensarbete MMK 2009:63 MFM129

Konstruktion och montering av ett gasspjäll för en HCCI-motor.

Àlex Poyo Muñoz

Godkänt	Examinator	Handledare
2009-Sept-18	Hans-Erik Ångström	Hans-Erik Ångström
	Uppdragsgivare	Kontaktperson
	KTH	Hans-Erik Ångström

Sammanfattning

Denna rapport handlar om införandet av ett gasspjäll i den HCCI motor som utvecklas på Kungliga Tekniska Högskolan (KTH) i Stockholm. Detta gasspjäll styr effekten och arbetssättet i motorn. Med en gasspjäll är det möjligt att byta från gnistantändning till HCCI-läge. Under projektet har många andra områden förbättrats, till exempel luft- och oljepump. För att dra slutsatser är det nödvändigt att analysera några av motorns data som insamlats under utvecklingen, såsom cylindertryck, insprutningsdata och tändläge. Man analyserade data under olika tidpunkter av motorns utveckling, med olika komponenter, för att uppnå olika prestanda i varje enskilt fall.

För att köra motorn i HCCI-läge är det nödvändigt att ha ett lambda-värde mellan 1,5 och 2. Även om resultaten visar att det är bättre att köra i "Pump + Throttle + Intake" kommer pumpen överbelastas på grund av ett extra tryckfall. Av detta skäl kommer är det nödvändigt att arbeta i "Throttle + Pump + Intake" i framtiden. Eftersom det är nödvändigt att minska insprutningstiden, av detta skäl, är det också viktigt att öka luftflödet. Vid sista konfigurationstestet var det inte möjligt att få mer luft från själva pumpen inom pumpens varvtalsgränser (max. 6000 rpm). Arbete över dessa hastighetsbegränsningar orsakade pumpöverhettning och minskade motorns prestanda. Därför rekommenderas att använda en kraftigare pump.

Däremot har en annan fil tagits fram för att få veta lite mer om beteendet i motorn. Denna fil kallas Task och ger användaren möjlighet att ta reda på kompressionsförhållande, kolvarnas lägen, portöppning- / stängning, hastigheter och många fler värden i motorn bara genom att ändra några värden.

KTH Industriell teknik och management

Master of Science Thesis MMK 2009:63 MFM129

Design and assembly of a throttle for an HCCI engine

Àlex Poyo Muñoz

Approved	Examiner	Supervisor
2009-Sept-18	Hans-Erik Ångström	Hans-Erik Ångström
	Commissioner	Contact person
	KTH	Hans-Erik Ångström

Abstract

This report is about the inclusion of a throttle in the HCCI engine that is being developed in KTH. This must control the power and working mode of the engine. With an air throttle it is possible to change the engine from spark mode to HCCI mode. During this project, many other aspects have been improved, such as air and oil pump. In order to take conclusions it is necessary to analyse some of the engine's data that was obtained during the development, such as cylinder pressure, injection pulse and ignition pulse. It was analysed different moments of engine's development using different components, to achieve different performances in each case.

To run the engine in HCCI mode it is necessary to have a Lambda value between 1.5 and 2. Even if the results show that is better to run in "Pump+Throttle+Intake", the pump has to overwork due to additional throttle resistance. For that reason it is necessary to work in "Throttle+Pump+Intake" in the future. But for that it is necessary to reduce the injection timing, for that reason it is important to increase the air flow. At the last configuration tested, it was not possible to get more air from actual pump, within the pump rotational speed limits (max. 6000 rpm). Working over these speed limits, caused pump overheating and decreased engine's performance. Then it is recommended to use a more powerful pump.

However, another file has been developed to know a little bit more about the behaviour of the engine. This file is called Task and gives to the user the possibility to know about the compression ratio, position of the pistons, port opening/closing, velocities and much more values of the engine just changing some values on it.

Acknowledgements:

This has been a period of time where I learned a lot, not only about the HCCI engine, also about the way to work in Sweden, which for me is the most distinguished country in Europe. For that reason, I would like to agree to Hans-Erik Ångström the possibility to work in this project; I could realize my dream of working with engines and at the same time improving the environment.

Furthermore I also have to agree to my working partners, which I have been working together every day during 6 month. They teach me a lot and I think we learned together in a nice work environment. Then, thanks to Kim Jaktlund, John Larsson and Marcus Bäcklin.

The guys of the workshop, Bengt and Tommy with their great productions, without them would be impossible to develop the engine.

During my last twenty days I could work with the engineer that is going to continue the project, Rafael Villasmil. I want also to agree him for helping me until the end to get my results. I'm sure he will improve the engine really fast, as we have been doing during these days.

Sofie Ljung made possible the translations into Swedish, thank you.

Is also very important to mention the company that made it possible, HCCI Technologies, thanks for the opportunity.

Last but not less important, to my parents Salvador Poyo Riba and Magdalena Muñoz Bruach. They gave me the possibility to live abroad to realize my dream. I could feel their support from the beginning to the end. I felt the same from all my relatives.

Contents

1. - Introduction

The main objective of this project is the inclusion of an air throttle in the HCCI engine, in order to control its power and working mode. With an air throttle it is possible to change the engine from spark mode to HCCI mode, but not the other way around. The throttle is a bit opened at the beginning to start the engine in spark mode (lambda 1) and once the engine is hot, it will turn to full opening and let the engine run in HCCI mode (lambda 1.5-2). As it is only needed two positions for this throttle, a solenoid is the responsible of realizing this movement. Also it was necessary to make a new intake where to fit the throttle, injector, and sensors.

The system needs a support where to put the throttle and the solenoid. In order to know the optimal different positions it was fundamental to perform tests and conclude with good result in the engine's behaviour. The throttle gives the possibility to run the engine safely in spark mode, controlling the amount of air and consequently the delivered power. The HCCI mode should then be run with open throttle or very little closed throttle. Then in HCCI mode the injected fuel can be the same as in spark mode and the Lambda value will continue being high.

The first idea before ordering manufacturing of a special throttle was the use of an existing throttle of a small 4-stroke injection engine. The reason of using this system as a provisional solution is that it was going to be used in a 50 cc engine with injection; hence it was needed the most accurate components to get best performance. Nowadays there aren't many engines that accomplish those requirements, for that reason it was difficult to find the most suitable one. After several experiments to find the most suitable device, it was found and selected one throttle belonging to Honda 50cc 4-stroke motorbike called Ruckus (USA model) or Zoomer (Japanese model).

In order to take conclusions is necessary to analyze some of the engine's data that was obtained during the development, such as cylinder pressure, injection pulse and ignition pulse. It was analyzed different moments of engine's development using different components, to achieve different performances in each case.

In the second part of the project the objective was to analyze the behaviour of the engine for different conditions that could be arranged. There it was elaborated a test procedure and further result analysis for this experiments.

This project was developed together with collaboration of three other students at KTH. During project several changes and improvements were made for engine's development and optimization of performance.

Another task included in this project, was to run this HCCI engine in Shell Ecomarathon competition that took place at the "Eurospeedway Lausitz" (Germany).

2. - Description of the working system

2.1 – HCCI Engine:

HCCI: Homogeneous Charge Compression Ignition. This engine can work with spark plug, as a normal Otto engine and also in high compression, as a diesel engine. The engine displacement is 49cc and uses two opposite pistons inside a single cylinder. Each piston has its own crankshaft connected to each other through two gear wheels. The engine works as a two stroke, so the ports are cast on the wall of the cylinder instead of having a cylinder head with valves. For that reason the engine does not need camshaft to open and close valves. It uses direct injection, but the possibility to work with port-injection exists. One of the biggest disadvantages from this design is that it is necessary to have an air pump to provide the air flow into the combustion chamber. The most outstanding characteristic is the patented system to change the compression ratio from 10:1 to 26.7:1 (depending on the pistons height), which gives lots of working possibilities. The engine runs without spark plug when it is working on high pressures. The objective of this engine is that in this mode it requires less fuel for the same amount of air, thus the Lambda value increases, which mean that the emissions are lower.

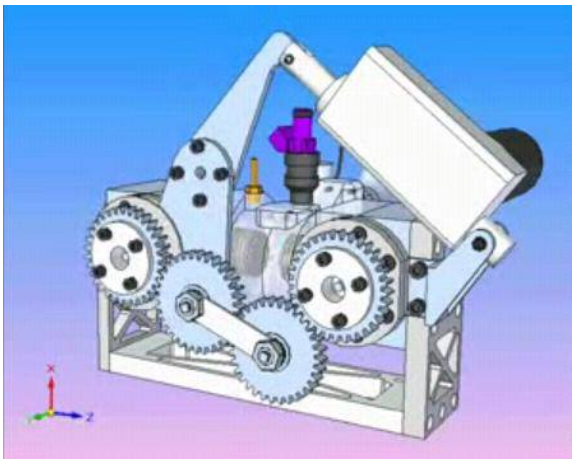


Figure 1: Back side of HCCI.

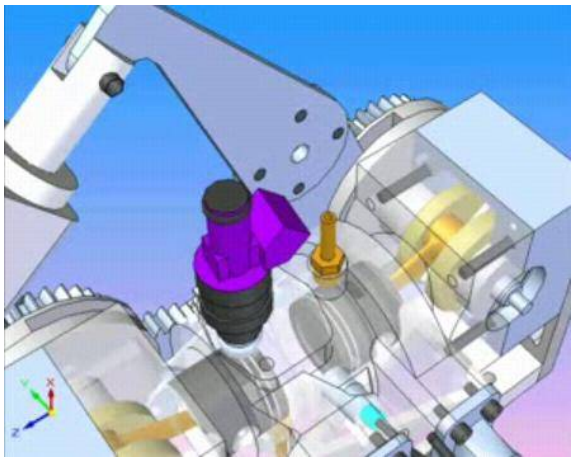


Figure 2: Top view of HCCI.

A high compression ratio inside provokes the mixture to ignite by itself. This engine is able to work in a compression ratio between 10:1 to 26.7:1. For that reason it cannot work in 100% "spark mode", therefore it will have sometimes auto ignitions. Working in “spark mode”, temperature increases and the engine is then able to work in HCCI mode. This means that the spark plug is not necessary anymore. In this mode the fuel amount that the engine needs is lower in relation to same amount of air as before. This increases engine’s fuel efficiency and decreases the emissions (lambda increases). When engine works in HCCI mode it operates lean and thus with lower power. But when the fuelling is close to the stoichiometric fuel ratio, power generated is much higher. This could cause overload for electrical components in the hybrid system. This happens when a throttle is required.

2.2 – HCCI Engine diagram

The engine has two shafts connected to the crank shafts. In the intake crank shaft is connected to a pump, which is for oil and air. On the other crank shaft an electric motor is connected. An electric motor is used to run the engine without ignition and also as a brake to measure the power of the engine while it is working.

An air particle from the atmosphere comes into the pipe to cross the air flow meter. Before the air pump is necessary to connect an expansion volume that decreases the air pulses to get the right measurement on the air flow meter. Then the air pump sucks this particle in the engine through the throttle. After the combustion this particle crosses the lambda sensor in the exhaust and then it goes out to the atmosphere again.

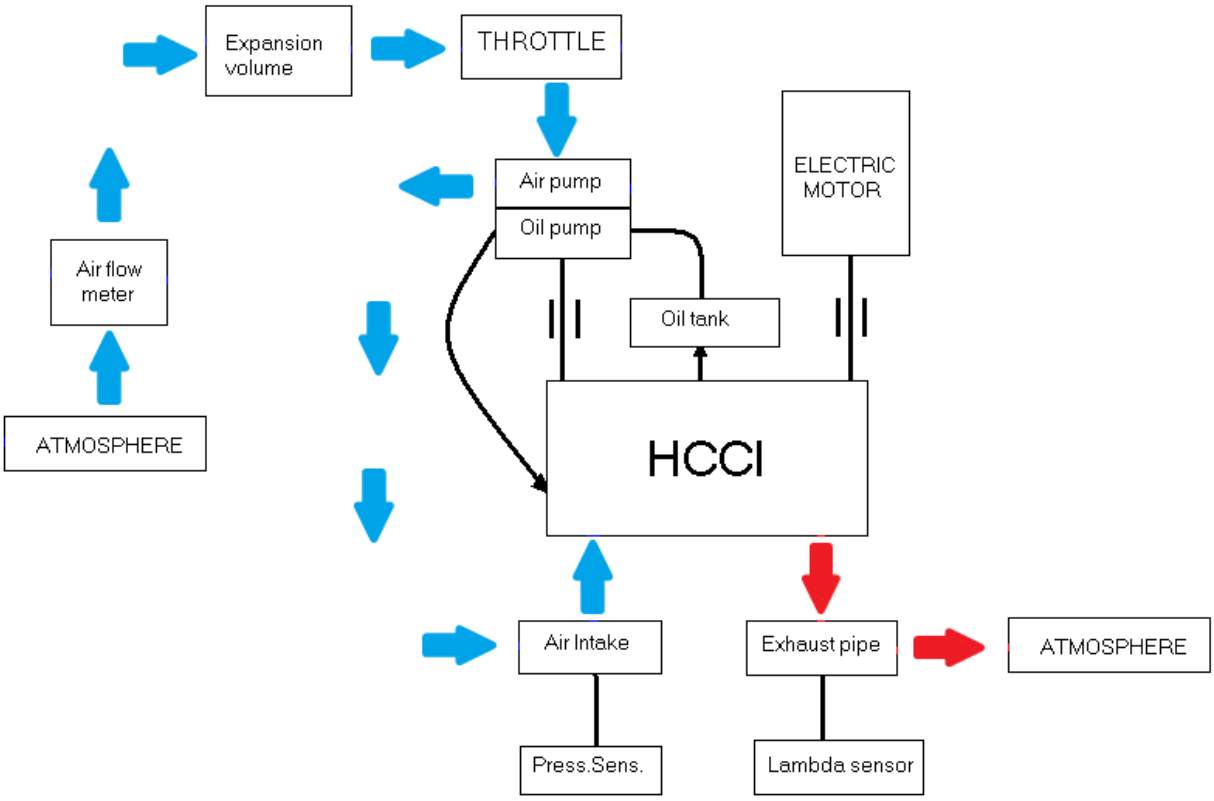


Figure 3: Working system diagram.

2.3 - HCCI Engine Modifications

2.3.1 – Air intake manifold

To test a port-injection system, a new air intake manifold, shown in **Figures 4** and **5**, was manufactured in aluminium. The injector is mounted in the top of the intake. Finally, this system was not used because the thickness of the hose needed is bigger than the intake's thickness.

Figure 4: Side view of the new intake manifold.

Figure 5: Front view of the new intake manifold.

2.3.2 – Oil tank

Designed in purpose for Shell Ecomarathon, this oil tank is fixed in the bottom of the engine and it is not moving around like in the previous system. It also gives a better refrigeration of the oil. The problem is that from the opposite side it is necessary to collect the oil that the engine blows into this tank. For that reason, oil is blowing out of this tank during the operation. This tank does not increase the performance of the small oil pump, which is not able to push enough oil into the engine, due the engine gets worm easily.

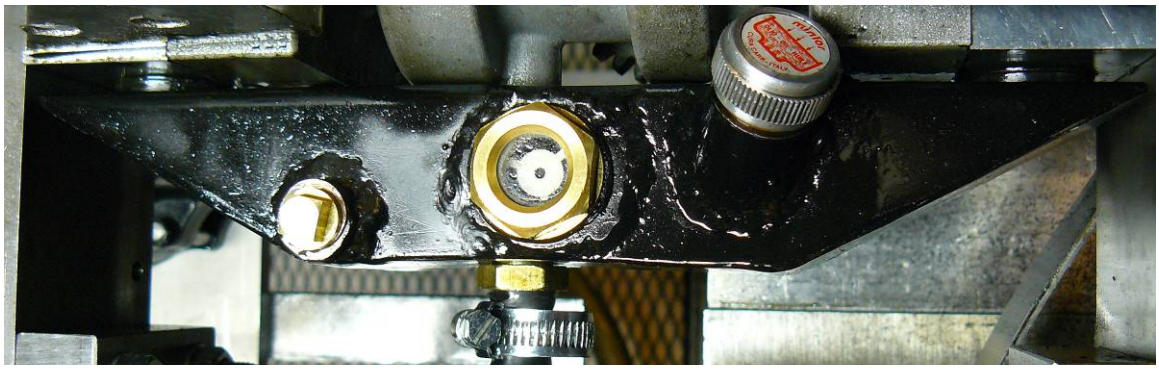


Figure 6: Front view of the oil tank, plug and purge holes.

2.3.3 – Exhaust pipe

Another problem with this engine is that a part of the fuel mix may go out of it without being burned, like in a normal two-stroke engine. For this reason a new exhaust intake was designed, following the manufacturing laws of two stroke exhausts. Its shape increases the diameter until an expansion chamber and then the diameter decreases again as shown in **Figures 7** and **8**. The idea is that the exhaust creates a frequency with the sound pulses going out from the exhaust port that makes the fuel go into the combustion chamber once again.

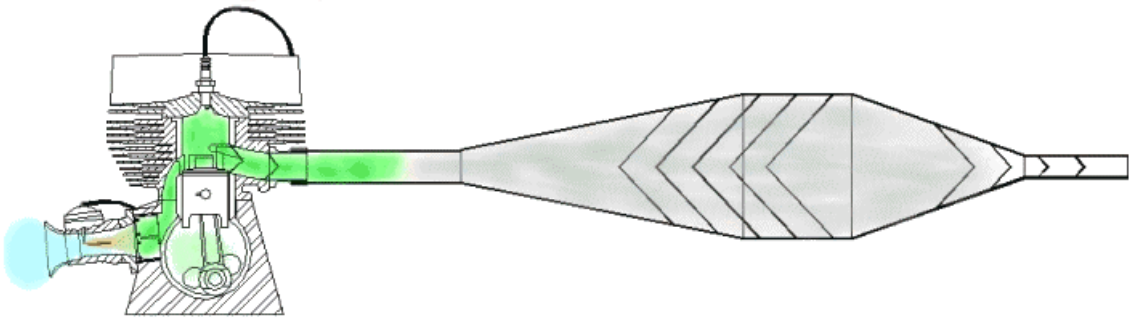


Figure 7: Example of an expansion volume of a two-stroke exhaust pipe.

Figure 8: Exhaust pipe manufactured for the HCCI including a Lambda sensor.

2.3.4 – Air/oil dual pump

The air/oil dual pump shown in **Figure 9** is divided in two sides, one of them is pumping air working as a roots compressor and the other side is an oil pump. The oil side shown in **Figure 10** is only pumping, is not able to compress it, but by changing one spring inside it is possible to calibrate the flow. This pump gives a high and constant air flow that makes the engine run on high rpm and smoothly. But it has a problem of temperature when it runs at high rpm (7000 rpm) because it becomes very warm and it is necessary to switch the engine off.

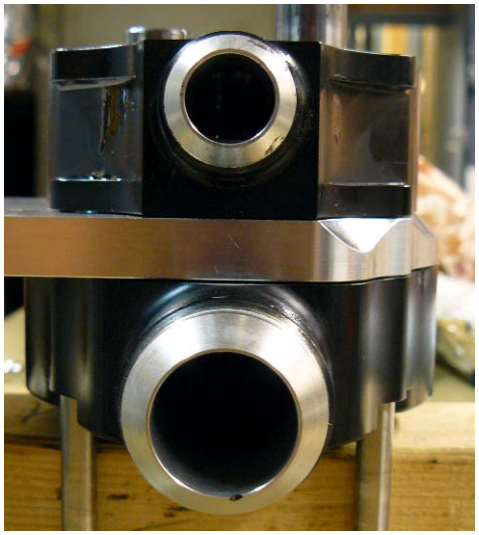


Figure 9: Current air pump, the bottom port is the air inlet and the upper port is the oil inlet.

Figure 10: Interior of the oil side of the pump.

2.3.5 – Lambda sensor

This sensor is one of the crucial components in the engine. Without it is difficult to know if the engine is working correctly in each of the two modes. In the spark mode the engine needs a Lambda value around 1 and in the HCCI mode this value must be between 1.5 and 2.

Figure 11: Lambda sensor added to the two-stroke exhaust.

2.3.6 – Expansion volume

An expansion volume is always needed in this case since the engine can send back pulses of air from the combustion chamber. These pulses will affect the values of the air flow meter. The expansion volume reduces these pulses.

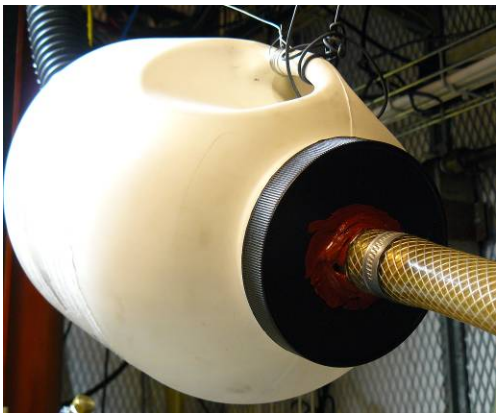


Figure 12: Plastic bottle used as expansion volume.

2.3.7 – Oil recirculation

The main function is to correct the faults of the oil tank. This system uses the air pump, which also works as oil pump. The pump gives a good recirculation of the oil and sends a constant oil flow into the engine to keep the optimal lubrication. The oil which is blown from the engine's scavenge is now collected in a second tank that leads air to the atmosphere through an air filter on the top. Further, this is connected to the oil pump on the bottom as well which impulses the oil into the engine again.

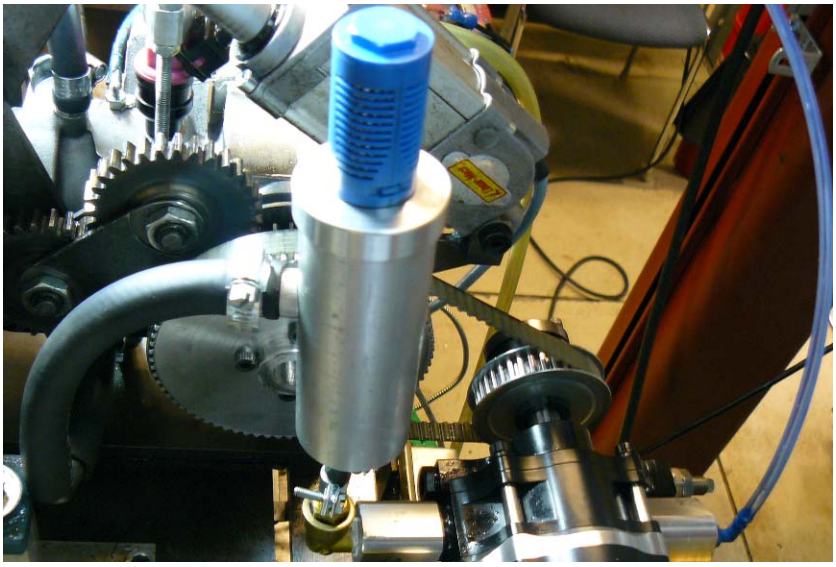


Figure 13: Oil recirculation system.

2.4 – Stock throttle

The throttle is originally from a moped called Honda Zoomer, which has already been converted to fuel injection. By using this new system it is possible to get much lower maintenance and fewer problems in the long run.

The information about Honda Zoomer's engine and transmission can be found in **Table 1**.

Table 1: Information about Honda Zoomer's motor.

Engine and transmission	
Displacement:	50.00 ccm (3.05 cubic inches)
Engine type:	Single cylinder
Stroke:	4
Power:	4.00 HP (2.9 kW)) @ 7500 RPM
Torque:	4.50 Nm (0.5 kgf-m or 3.3 ft.lbs) @ 5000 RPM
Compression:	12.0:1
Bore x stroke:	38.0 x 44.0 mm (1.5 x 1.7 inches)
Fuel system:	Injection. PGM-FI electronic fuel injection
Fuel control:	SOHC
Ignition:	Digital transistorised with electronic advance
Starter:	Electric & kick
Cooling system:	Liquid
Gearbox:	4-speed
Transmission type final drive:	Belt
More details	Consult a Honda repair manual.

The most important aspect of that engine is the low fuel consumption due to the PGM-FI system; as a result the emissions decrease as well. PGM-FI, suitable for use in four-stroke, 50cc scooters, presently marketed by Honda as "Clean 4".

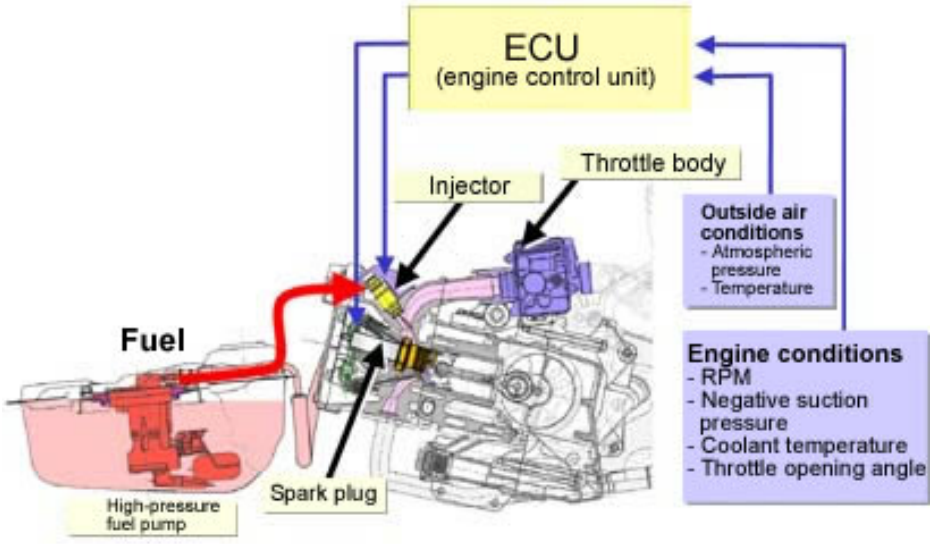


Figure 14: Complete diagram of Honda Zoomer's engine.

The electronically controlled fuel injection system (PGM-FI) with enhanced fuel consumption and cleaner exhaust gas has been developed for mass-produced four-stroke 50cc engines for the first time in the world. Through this technology, further reduction of fuel consumption and cleaner exhaust gas will be promoted for 50cc class engines which comprise the greatest sales in the domestic market.

Stock throttle from the Honda Zoomer 49cc:

Figure 15: Side view of the Zoomer's throttle.

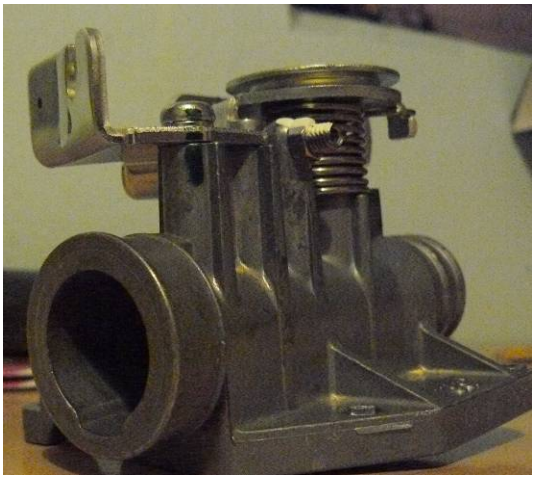


Figure 16: Front-side view of the Zoomer's throttle.

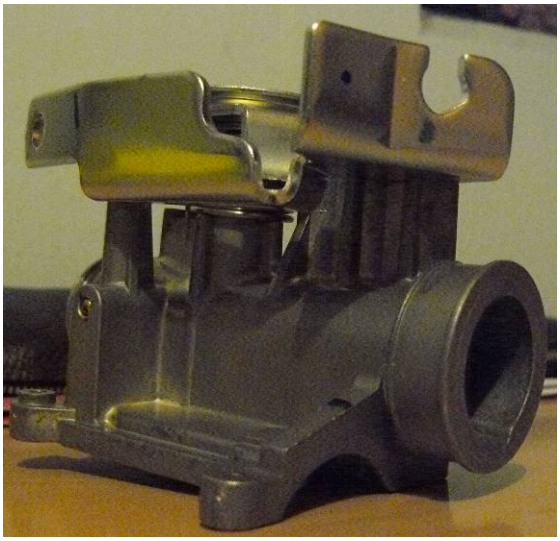


Figure 17: Front- side view of the Zoomer's throttle.

Figure 18: Bottom of the Zoomer's throttle.

Figure 19: Electronic Control Unit

It is possible to see in **Figure 18** the paths made for the air circulation in the bottom part of the throttle. The blue stuff is sealing used to obstruct the holes on it. As the Electronic Control Unit is not necessary in this case, it has been removed in order to reduce the weight and also to block the holes with a sheet of aluminium.

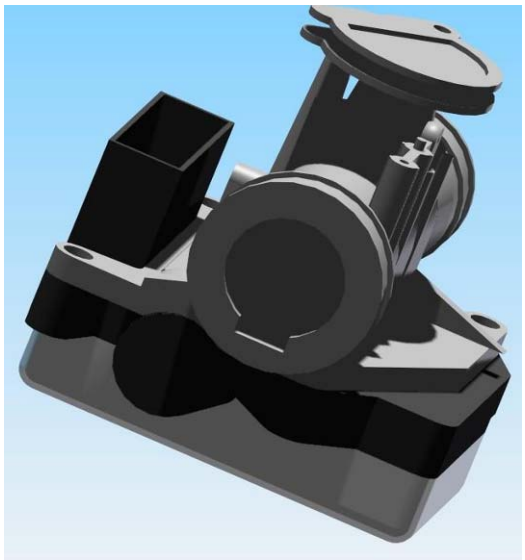


Figure 20: Throttle's CAD model with ECU included.

2.5 – KTH throttle, modified

The stock throttle is not useful for this project, for that reason it was necessary to modify it. Before finding the definitive one, different versions have been manufactured.

2.5.1 – Version 1

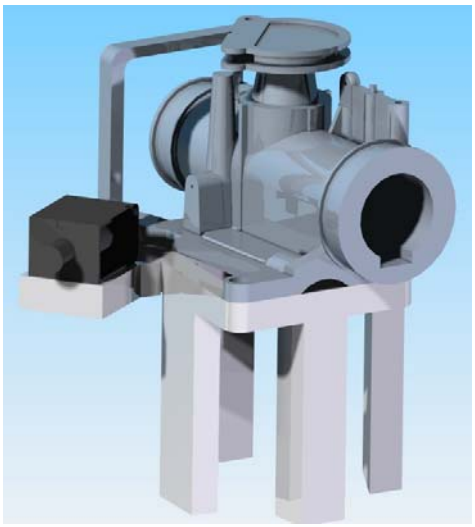


Figure 21: CAD simulation of the first support.

In this configuration the position of the solenoid and the arm were not compatible in length. This leaded to further development of the solenoid position.

2.5.2 – Version 2

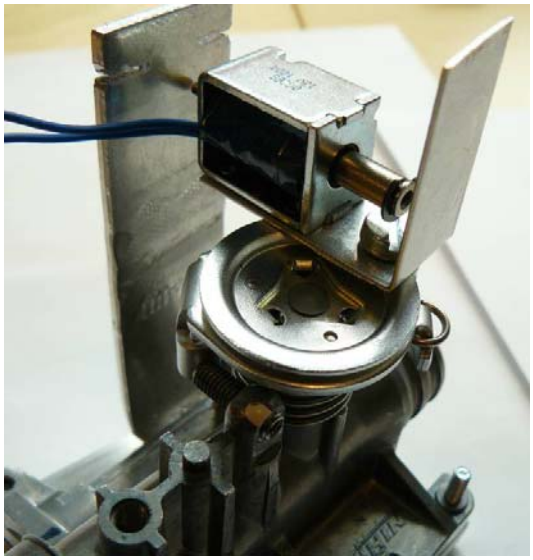


Figure 22: Second throttle developed.

Once the solenoid gets power is activated and knocks the wall as shown in **Figure 22**. This produces a backwards movement of the system. As a consequence, the throttle is opened. The stock spring takes charge of moving the system backwards to the initial position of the throttle. The problem with that mechanism was that the stock spring was too strong, even after cutting some of the spirals.

2.5.3 – Version 3

Figure 23: Bottom part of the support of the final throttle.

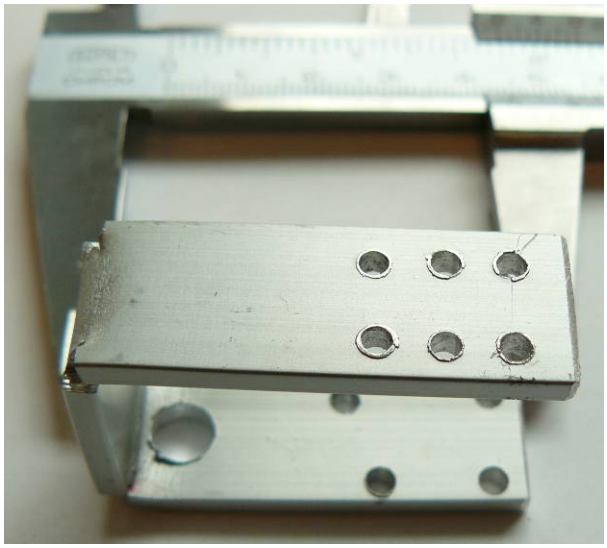


Figure 24: Base for the solenoid location.

Figure 25: Axle where the solenoid turns around.

Figure 26: Final throttle, front view.

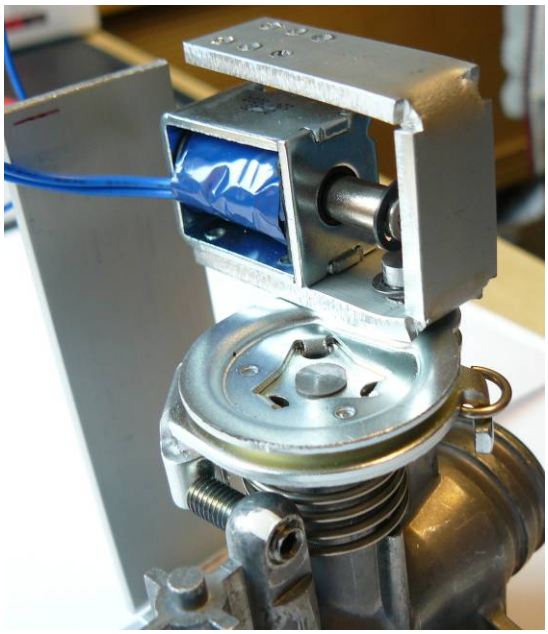


Figure 27: Final throttle, solenoid detail.

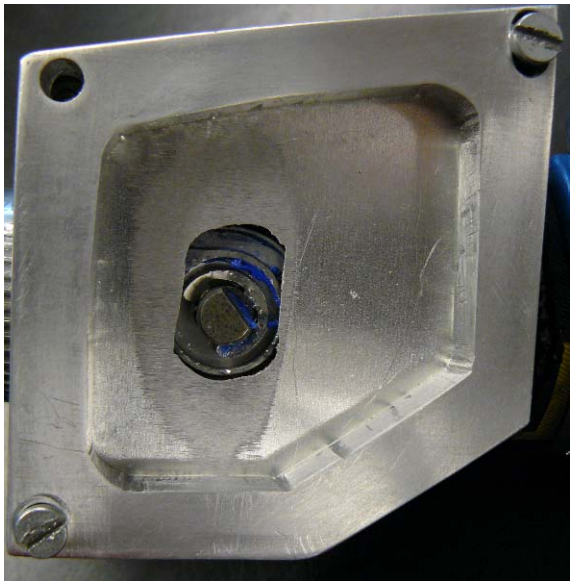


Figure 28: Final throttle, bottom view.

The final throttle design was based on previous a configuration, but with several improvements. A plate on the bottom was added to block the air flow from there as shown in **Figure 28**. The returning of the solenoid is done for two small springs.

Figure 29: CAD model of the final throttle.

2.6 – Inclusion of the throttle

Having a throttle creates two inquirers. It is important to consider this in order to add a throttle to the engine´s system. One is to use a port-injection, and the other is to refer to the position of the throttle.

2.6.1. - The use of a port-injection:

The engine was using the injector from a Renault Twingo in direct injection. The throttle from Honda Zoomer uses its own injector as shown in **Figures 36** and **37**. This is more appropriate for the HCCI engine since it is a 49cc block and is possible to inject very small amounts of fuel. The injector has been used in port-injection mode, but the results are not favourable compared with the results of the previous system. The problem is that after some test the engine and the intake manifold were full of fuel. The spray's angle of the Honda injector is too wide, for that reason the fuel kicks the walls of the intake manifold instead of going directly inside the cylinder. It results in drops all around the surface of the manifold, due the air can't mix properly with the fuel. In order to clean the engine was necessary to remove the spark plug and the Twingo's injector placed on the top and run the engine with both cavities opened to let the waste go out. A consequence of running in port-injection is that the tip of the Twingo's injector was burned.

The reason is that with this injector switched off, the fuel doesn't flow through it and is not refrigerated as shown in **Figure 36** and **37**.

Since the aim of port-injection was not accomplished, it was decided to apply some changes. Another Twingo's injector was mounted in port-injection, in this occasion the fuel was kicking directly on the piston side. Both situations decreases the yield of the engine, thus the conclusion is to continue with direct injection.

Working in direct injection is possible to observe that the engine works better when the cylinder block temperature is high; this is because then is easy to mix the particles of fuel and air. But in this point the temperature is too high and the automatic temperature control turns off the engine for safety reasons.

2.6.2 – Position of the throttle respect the air pump

One important feature of HCCI engine is that it uses an air pump to impulse air inside the combustion chamber. Hence is important to know the correct position of the pump, since there are two different possibilities. The first one is to put the pump before the throttle, then an air particle would go from the atmosphere to the air pump, after through the throttle and finally inside the intake manifold. The other possibility is to have the pump after the throttle, between the intake manifold and the throttle.

With the experimental results shown in **table 3** it was concluded that is better to connect the pump before the throttle. But this is a wrong conclusion, it is better for the air pump to connect the throttle before it; otherwise the pump has to work a lot to push the air through the throttle. It makes the air warmer, reducing the mass of oxygen that goes into the engine. It produces low quality combustion.

2.6.3 Throttle solenoid

A solenoid uses the power of a magnetic field to move forward a cylinder, which gives to it only two positions. Once it is connected to the electric power the cylinder moves forward and once is disconnected a spring moves it back. This mechanism is the used to open and close the throttle.

The magnetic field inside a solenoid is given by:

$$B = \mu_0 n I = \mu_0 \frac{NI}{h}$$

where:

$\mu_0 = 4\pi \times 10^{-7}$ **henries per meter (H x m)**
B is the magnetic field magnitude in **teslas (T)**
n is the number of turns per **meter (m)**
I is the current in **amper (A)**
N is the number of **turns**
h is the length of the solenoid in **meters (m)**

This model selected satisfies a good ratio between performance and price.

Selected solenoid specifications:

Voltage: 12 v
Max. advance: 9 mm
Max. force: 4,4 N

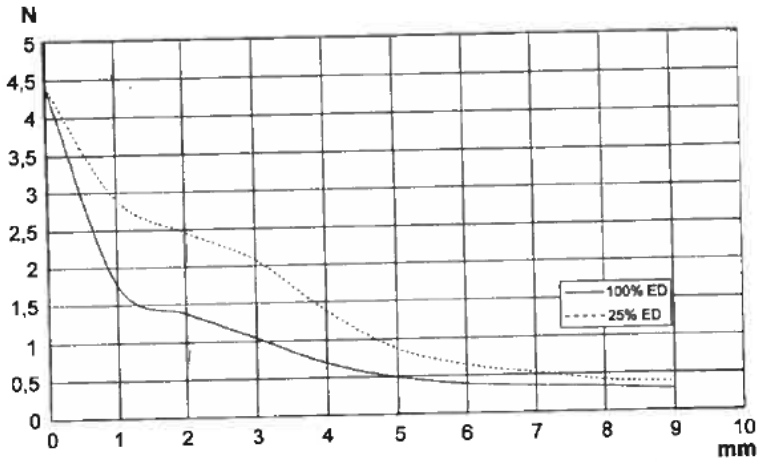


Figure 30: Force vs. advance of the solenoid.

Modifications:

The original forward movement of the solenoid is not enough to open the throttle to 100%, for that reason was necessary to modify it. As shown in the **Figure 31** and **32** the modification gives 5mm extra of advance.

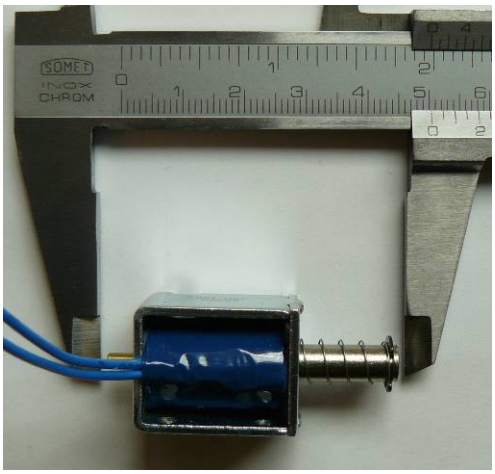


Figure 31: Solenoid before modification.

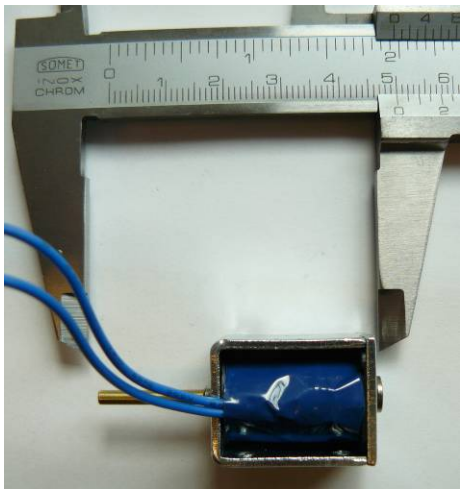


Figure 32: Solenoid after modification.

Drilling a bigger hole eliminates the obstacle that didn't allow the complete advance. It is possible to see in the **Figure 33** the difference between both diameters.

Figure 33: Comparison of modified and stock diameters.

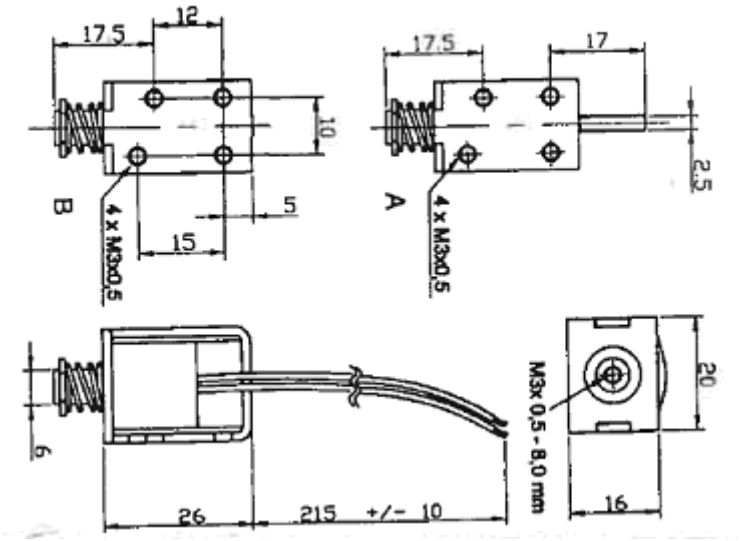


Figure 34: Sizes and views of the solenoid.

2.7 – Injectors

It was necessary to test a variety of injectors in order to work with different injection timings, pressures, amount of fuel to know which gives the best performance.

2.7.1 Renault Twingo's injector

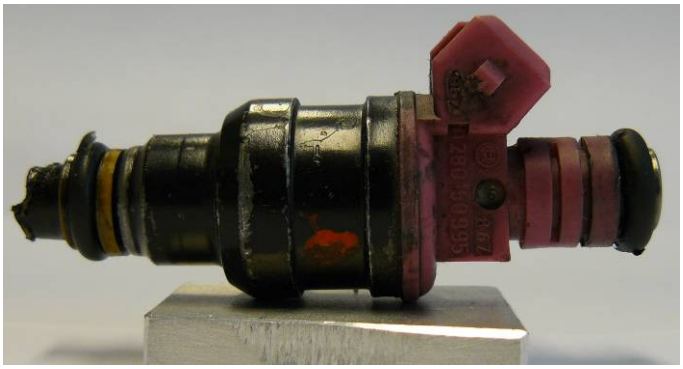


Figure 35: Side view of Twingo's injector.

Figure 36: Front view of Twingo's injector.

Reference number: 0280150995

cc/min at 3bar: 90

Resistance (ohm): 14,5

2.7.2 Honda Zoomer's injector

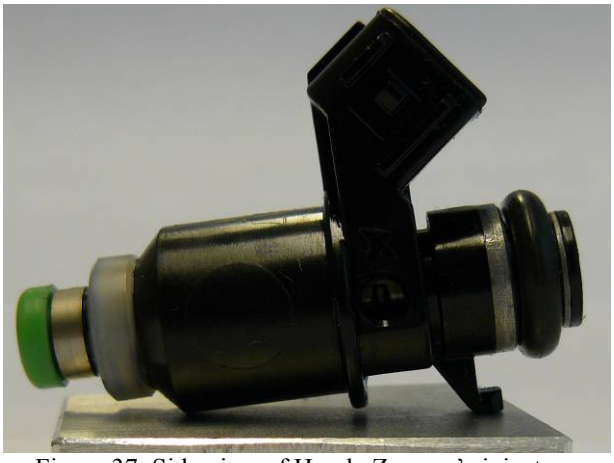


Figure 37: Side view of Honda Zoomer's injector.

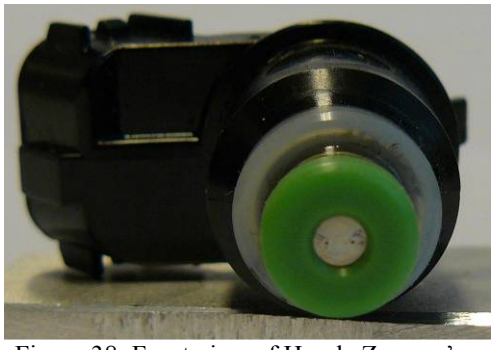


Figure 38: Front view of Honda Zoomer's injector.

Reference number: WF 17 ABIV
Resistance (ohm): 11,8

2.5.3 Shell Ecomarathon's injector

The delivered amount of fuel (**table 2**) was smaller than the one that we need to run the engine.

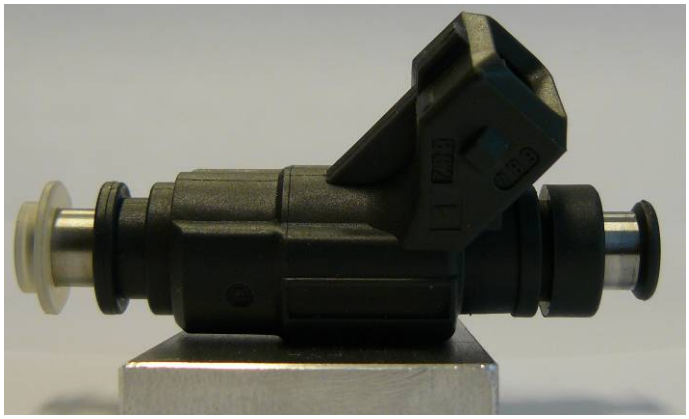


Figure 39: Side view of Ecomaraton's injector.

Figure 40: Front view of Ecomaraton's injector.

Table 2: Bosch B280434801-01 injector

Delivered fuel flow	10 g/min
Pressure	300 kPa
Resistance	14,5 Ohm
Inductance	15 mH
Tension	12 V
Injection timing	1-9,8 ms
Injection amount	0-1,5 mg/inject.

2.7.4 Volvo's injector

Model from Bosch with similar shape as Twingo's injector, but instead of having two sprays it has only one. Is not useful in this engine because the amount of fuel injected is too high.

Figure 41: Side view of Volvo's injector.

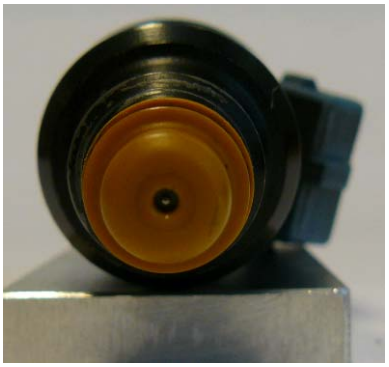


Figure 42: Side view of Volvo's injector.

Reference number: 0280150740

cc/min at 3bar: 156

Resistance (ohm): 15,9

Figure 43: Visual comparison of the injectors sorted by size and length.

Finally Twingo's injector was selected due to the best operational performance among available injectors, to achieve the lowest fuel consumption possible.

2.8 – Throttle calibration

The throttle can be opened from a 0% to 100%, the system used is a disk with a shaft in the middle that opens and closes. A screw was used to hold the throttle in different positions. The distance taken for each position goes from the end of the screw to the edge of the nut as is possible to see in **Figure 44**.

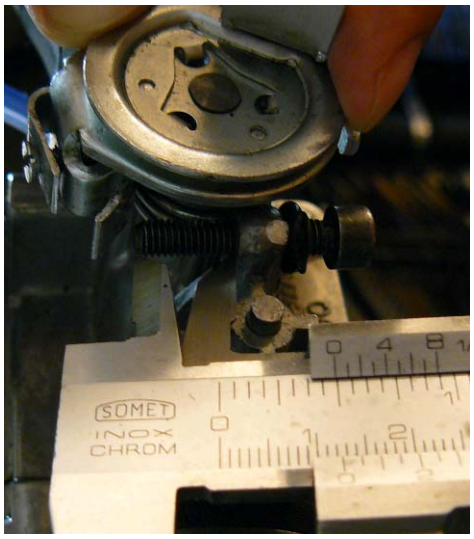


Figure 44: Throttle's opening calibration.

3. – Test procedure

To get the results the first step is to situate the throttle in the working line. For this there are two possibilities and for each one the throttle was opened 25%, 35%, 50%, 75% and 100%. Then the injection timing and the phase difference are the parameters to change. It is important to change only one of them each time and then write down the results. For example change injection timing and keep static phase difference or the other way around.

For the basic configuration of the engine a gear ratio between engine's crankshaft and air pump axle of about 1:2 was used. It means that the air pump was spinning up to 10000-12000 rpm when engine's speed is reported at about 5000-6000 rpm. As the air pump operational limit was about 6000 rpm, is believed that overheating of air could cause differences in results.

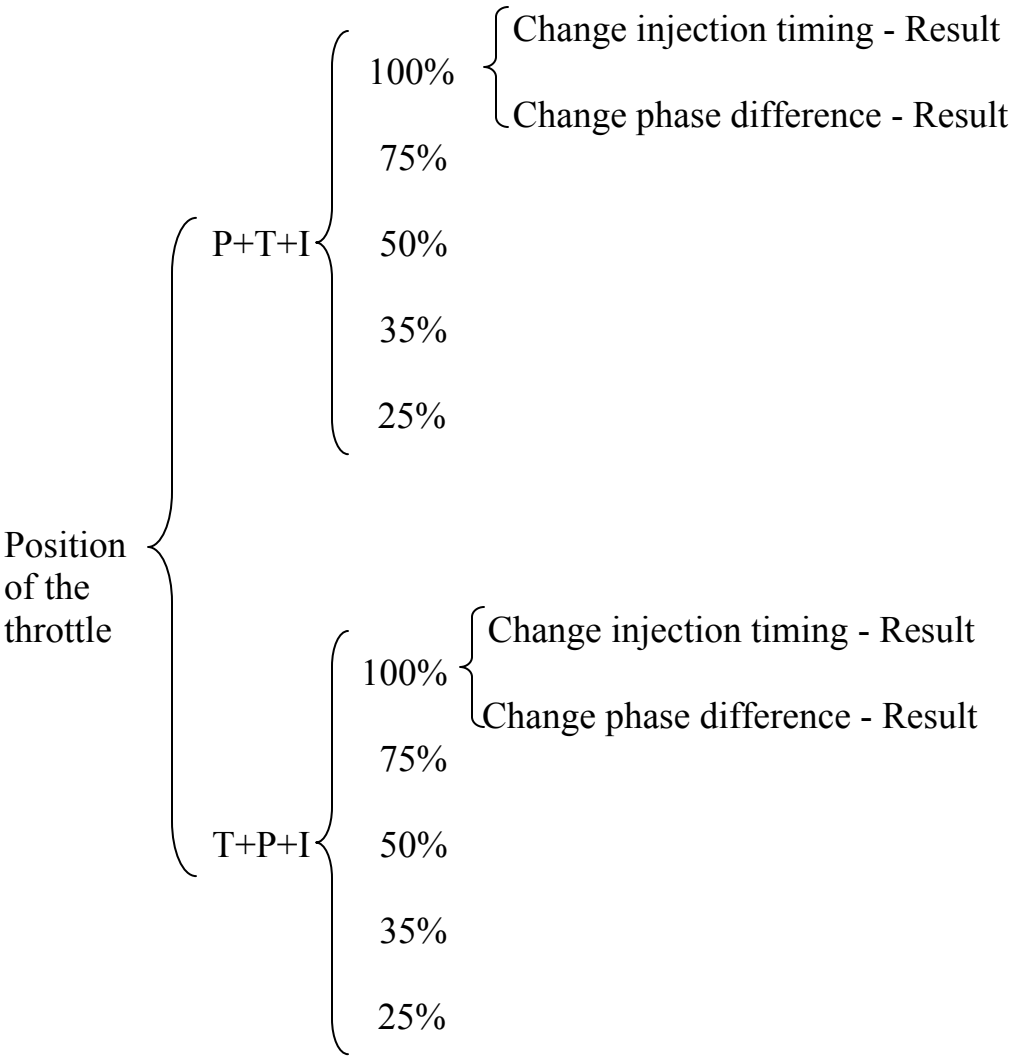


Figure 45: Procedure of testing the engine.

T = Throttle
I = Intake
P = Pump

In 100% is necessary to have λ between 1.5 and 2 to jump to HCCI mode. On the other hand, when the engine has to work in spark mode, the throttle must have a small opening in order to block the air flow into the engine and get a λ = 1.

4. – Results

The results from experimental tests are shown in **Table 3**.

Table 3: Results taken with the throttle.

Throttle position	Throttle Opening (%)	Distance Opened (mm)	Test num.	Lambda	Inj. Tim. (ms)	Phase dif. (deg)	rpm	Power (kW)
P+T+I	100	Max position	1	1.5	2.4	9	4000	0.2
			2	1.2	3.5	9	5600	0.4
			3	1.4	3.5	15	4700	0.3
			4	1.46	3	17	3900	0.2
			5	1.4	3.6	17	4200	0,3
			6	1.2	2.2	12	3500	0.2
			7	1.1	2.2	5	3400	0.2
			8	1.2	2.6	5	3600	0.3
			9	1.2	2.6	12	3700	0.3
			10	1.3	2.1	3	3400	0.3
	75	15	11	1.1	3.3	12	5500	0.4
			12	1	3.3	9	5500	0.5
	50	8	13	1.2	2.6	15	3600	0.2
			14	1.3	2.6	8	3800	0.3
	35	6.5	15	1	2.7	12	3800	0.2
			16	1	3	12	5000	0.5
			17	1.2	3	18	4000	0.3
	25	5	18	1	2.7	12	3700	0.2
			19	1.1	2.7	9	4100	0.3
			20	1.1	3	12	5400	0.4
T+P+I	100	Max position	21	1.3	2.2	12	4200	0.3
			22	1.28	3.1	12	4800	0.3
			22	1.2	3.6	12	5000	0,4
	75	15	23	1.2	3.2	12	4200	0.3
	50	8	24	1	3.4	12	5300	0.4
	35	6.5	25	1	3.6	12	6500	0.6
	25	5	26	0.9	3.2	12	6300	0.6

T: Throttle
P: Pump
I: Intake

With the experimental results shown in **table 3** it was concluded that is better to connect the pump before the throttle. But this is a wrong conclusion, it is better for the air pump to connect the throttle before it; otherwise the pump has to do a lot of unnecessary work to push the air through the throttle. Due to quality combustion criteria, it makes the air warmer, reducing the mass of oxygen that goes into the engine. It produces low quality combustion.

5.- Discussions

Test show that at 35% of throttle (spark mode) and with **T+P+I** the power and the rpm are higher, but in **P+T+I** the injection timing is lower, consequently the fuel consumption is also lower, but the quality of the combustion is lower as well.

Best performance to start is in spark mode corresponds to test **16** with 35% opened throttle. Lambda value is exactly 1 and the power and the rpm are higher than in other configurations. On the other hand in test **15** the injection timing is lower, but the power is more than twice lower.

On the other hand, it is possible to see that the engine has a good performance in test **26** running in **T+P+I**, but the injection timing is very high.

The engine runs very smooth and stable in configuration number **9**, but is not a recommended configuration due to the low power delivered and the lambda value far from 1.5.

On the other hand is possible to see a lambda value close to 1.5 in test number **4**, but the rpm and the delivered power are very low.

The lowest injection timing and lowest phase difference is used in test number **10**. Even in this case the lambda value is still too low to run in HCCI. The rpm and the power are also low. Decreasing more the injection timing the engine switches off itself.

6. – Conclusions

In T+P+I the injection timing always needs to be very high, for that reason the first impression is that it is not as interesting as P+T+I. Then in order of results, it is more interesting to run the engine configured in P+T+I. The best performance to start the engine in spark mode is number 16 and the best results with 100% of opening are in configuration number 2.

To run the engine in HCCI mode is necessary to have a Lambda value between 1.5 and 2. This is not possible with the configuration that is being used now (**P+T+I)**, even without the throttle was not possible.

In order to know the air flow that the engine needs to get $\lambda = 2$, some calculations has been done. The result shows that the flow has to be higher than the one that the pump can deliver with gearing used (one crank revolution is two revolutions of the pump). Is not possible to increase the actual gearing (1:2) because the optimal speed of the pump is 7000 rpm, and the engine has been run up to 10.000 rpm.

Calculations of air flow mass for an injection timing of 3.6* ms and $\lambda = 2$:

- Using a log file of 60 seconds and measuring the fuel consumed: 3.6 ms = 23.5 g/min.
- $Air\ Flow\ Ratio = \frac{X}{\text{Fuel flow}}$ Where X is Air Flow Mass.
- $\lambda = \frac{AFR}{14.7\ kg\ air/kg\ fuel}$.
- Then: $Air\ Flow\ Ratio = \frac{X}{23.5\ g/min}$ thus

$$2 = \frac{\frac{X}{23.5\ g/min}}{14.7\ \frac{kg\ air}{kg\ fuel}}$$ and finally solving:

X = Air Flow Mass = 690.93 g/min.

The delivered air during the test was around 220 g/min, that is the reason why the engine is far away from getting a high lambda, then far from HCCI. To increase the lambda value is necessary to increase the Air Flow Ratio and there are two possibilities. The first one is to hold the fuel flow while the air flow is increased. The second possibility is to decrease the fuel flow and hold the air flow. Apparently the easiest solution is to run the

engine at low injection timing, but the test show that this is not possible. The reason is that the ratio between air flow and fuel flow is proportional to the lambda value. This means that if we increase twice the injection timing for the same air flow, the lambda value will be twice lower. It means that for our air flow of 220 g/min the fuel flow needed to get $\lambda = 2$ is 7.48 g/min, this is a very low injection timing of 1.14 ms. The engine is not able to run with such a low injection timing. Then, the other solution is increase the air flow, but for this is necessary to increase the rpm of the air pump, which is now working at its limit of rpm. But it is possible to add more stages to the pump, which is now in number 1. This will give the possibility to get the necessary flow.

Even if the results show that is better to run in P+T+I, the pump suffers a lot pushing the air through the throttle. For that reason is necessary to work in **T+P+I** in the future. But for that it is necessary to reduce the injection timing, for that reason is important to increase the air flow. At the moment this is impossible with the pump that is being used, because when the engine is running at 6000 rpm, the pump does it at 12000 rpm. This speed is too high for the air pump giving as a result an overheating of it, which automatically decreases the engines performance. Then a recommendation is to use a pump more powerful.

Another aspect to improve is the injection system. It is necessary to work more on it. Direct injection is good because the fuel gets hot and then is easy to burn. But it is still considered that port-injection could be better, because the mixing air/fuel is better, closer to the homogeneous. The intake port is squared and it becomes in losses. Moreover it is really difficult to develop a proper intake manifold with this rectangular shape.

A file that contains the evolution of the engine's configuration and improvements has been developed. It has been given to the engineers that will continue with the project.

*This was the current value of injection timing during the test, due to the configuration used in the engine. But doing some changes in the engine it is possible to reduce this value. The calculations are the same, but consequently the airflow will be lower.

7.- References

1. - A study of HCCI combustion using a two-stroke gasoline engine with a high compression ratio.
Akira Lijima, Takashi Wanabe, Koji Yoshida and Hideo Shoji.
Nihon University.

2. - High specific power output direct injection two-stroke engine applications.
Rodney Houston, Greg Bell and Steven Ahren.
Orbital Australia Pty.Ltd.

3. - The potential of enhanced HCCI/CAI control through the application of spray guided direct injection.
Simon Brewster, Geoffrey Cathcart and Christian Zavier.
Orbital Corporation Ltd.

4. - Development of 2^2
David Larsson

5.- University researchers: Tomorrow's vehicles will be different.

http://www.epinions.com/review/2006_Honda_Ruckus/content_363108732548
http://www.bikez.com/motorcycles/honda_zoomer_2008.php
http://motos.autocity.com/secciones/noticias_revista/presentaciones/autocity/honda_zoomer_07_2004/index.html?cod=2032
http://world.honda.com/motorcycle-technology/pgm-fi/p6.html

Appendix 1- Calculation's file

1.-Measurements of the engine

1.1.- Cylinder block:

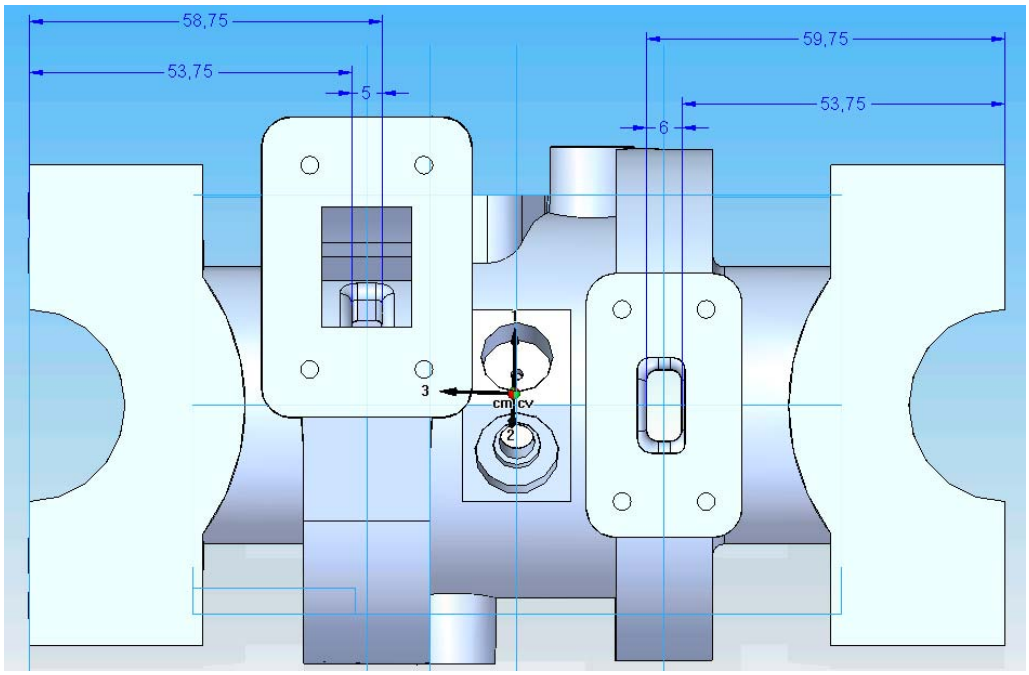


Figure 46: Ports side of the engine's CAD modelling.

1.2.- Distance between the crank and the piston axle when the engine is in TDC:

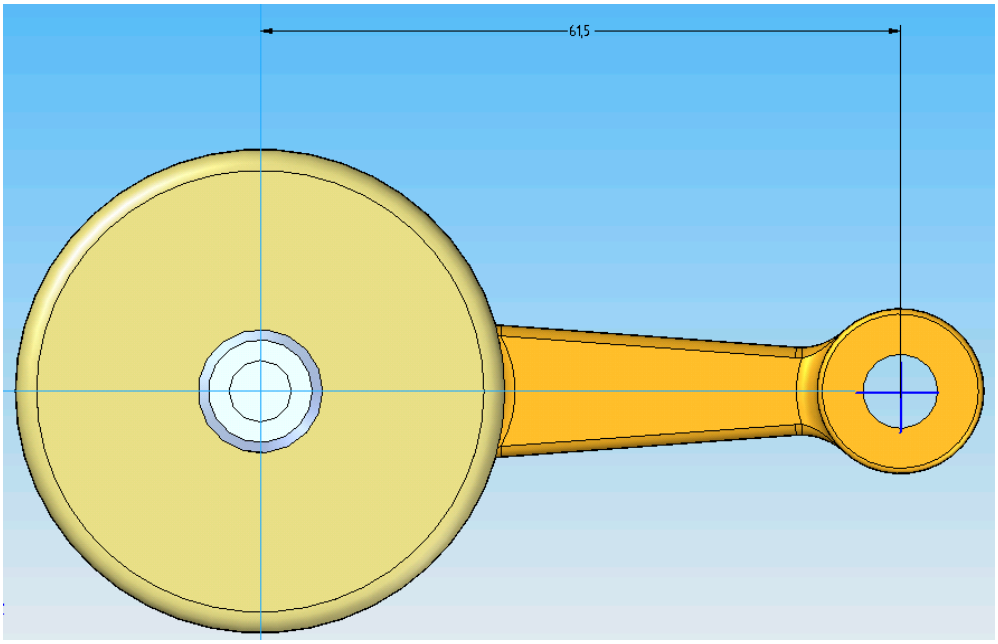


Figure 47: CAD modelling of the crank shaft with the rod connection I TDC (61,5mm).

1.3.- Distance between the crank and the piston axle when the engine is in BDC:

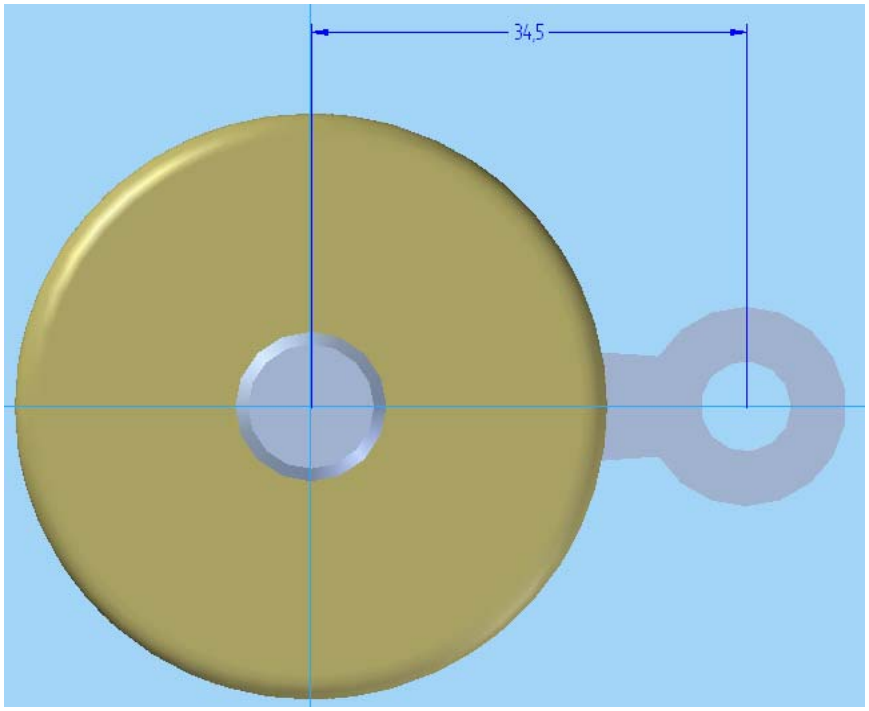


Figure 48: CAD modelling of the crank shaft with the rod connection I BDC (34,5mm).

1.4.- Distance between the axle of the crank shaft and the connecting rod:

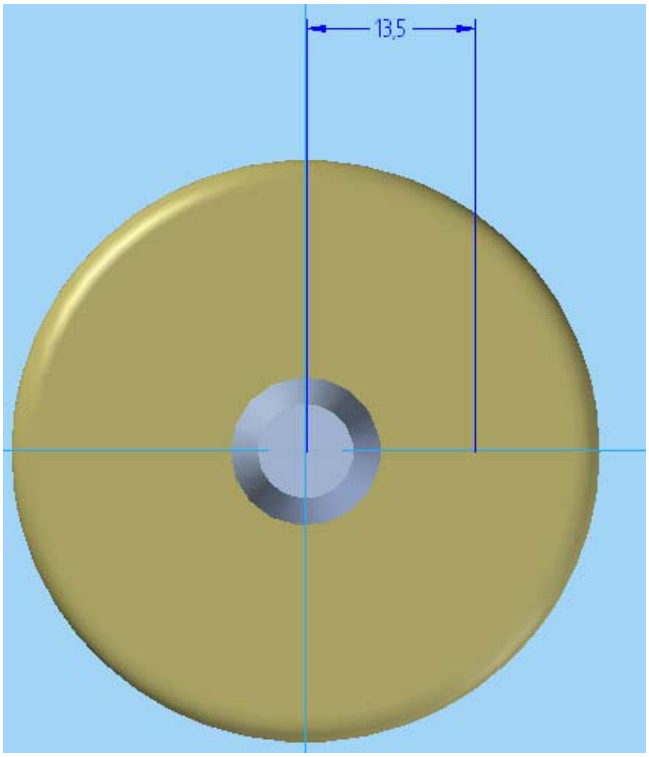


Figure 49: CAD modelling of the crank shaft.

1.5. - Length of the connecting rod:

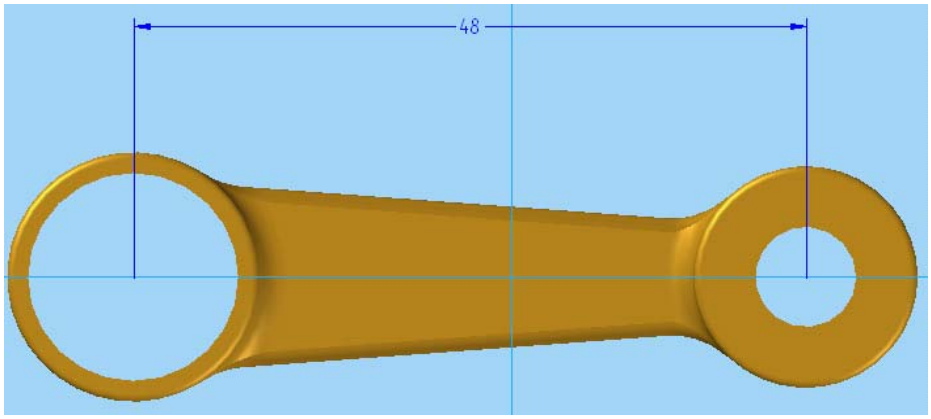


Figure 50: Connection rod.

2.- Procedure of the calculations:

2.1.- Introduction:

With the file of the calculations, it is possible to know important information about the performance of the engine for each crank angle degree. The user must introduce some previous parameters that can be modified on the engine every time that it is run. The information that is possible to change is:

- Phase different between pistons.
- Height of each piston.
- RPM.

All the results are obtained automatically, only changing the values mentioned before, but for the cylinder pressure is different, because the file uses a real pressure as initial pressure. This is found from the engine data given by the program used during the project to get results from the engine.

2.2.- Some numbers to understand the engine:

When the head of right piston is at 53,75 mm from the centre of his crank, the exhaust port starts to open and when the position is 59,75 mm the exhaust port is completely closed.

When the head of the left piston is at 53,75 mm from the centre of his crank, the inlet port starts to open and when the position is 58,75 the port is completely closed.

This information is valid for all pistons' height and phase difference.

2.3.- Cylinder pressure:

There are some values that are not included directly on the calculations and they will affect them directly. The initial pressure (P1) is found on the data program from real working cycles of the engine. This file contains all the information of the engine for some cycles and will be affected for some parameters such as the different delivered ratio of the air pump, the injection timing, ignition timing, phase difference and others. Thus is necessary to change some values manually on the calculations file. These are:

- V1: random volume to use it as initial volume.

- P1: pressure at the crank angle of V1, will be the initial pressure.

It is necessary to take both values for the same crank angle.

Two different cases are in consideration for the pressure:

- 1.1 Without combustion. -50deg 3,56bar standard deviation of 0,66

- 1.2 Combustion. -50deg 2,03bar standard deviation of 0,79

These values are valid for the log 55 of week 7 for combustion and 52 without combustion, for 0deg Phase difference, 0,25 height of pistons and of a pump delivered ratio of 60%.

2.4.-Procedure:

To start with the description of the procedure it is necessary to know the name of all the new concepts used.

Table 4: Description of the abbreviations in the calculation's file.

Names	Description
EPP	Exhaust Piston Position(mm from crank)
IPP	Intake Piston Position(mm from crank)
ITSO	Intake Total SurPhase Opened(mm2)
ETSO	Exhaust Total SurPhase Opened(mm2)
Xmax	Maximum Piston Displacement(mm)
TEPO	Time Exhaust Port Opened(sec)
TIPO	Time Intake Port Opened(sec)
V	Piston Linear Velocity(m/s)
cr	Compression ratio
a	Distance Intake opened(mm)
b	Distance Exhaust opened(mm)
c	Distance between ports on Max.Comp.(mm)
d	Distance between pistons when both ports are already closed(mm)
V1	Vol. when bot ports are already closed(cm3)
V2	Vol. of combustion chamber(cm3)
P1	Initial Pressure
P2	Cylinder pressure
V1'	Initial Volume in a decided angle, for calculations
Max. CR:	Max. compression ratio
Position	Crank Angle for the exhaust crank shaft is
Xapp1	Distance of intake pistons head from the centre of the cylinder.
Xapp2	Distance of exhaust pistons head from the centre of the cylinder.

IPP = Xmax + Piston Height – Xapp1
EPP = Xmax + Piston Height – Xapp2
ITSO = a*12*5 because the engine has 5 Intake ports
ETSO = b*12*4 because the engine has 4 Exhaust ports
V = rpm*0,017453*360/60
TEPO = 0,006/V
TIPO = 0,005/V

Intake Total Surface Opened (ITSO):

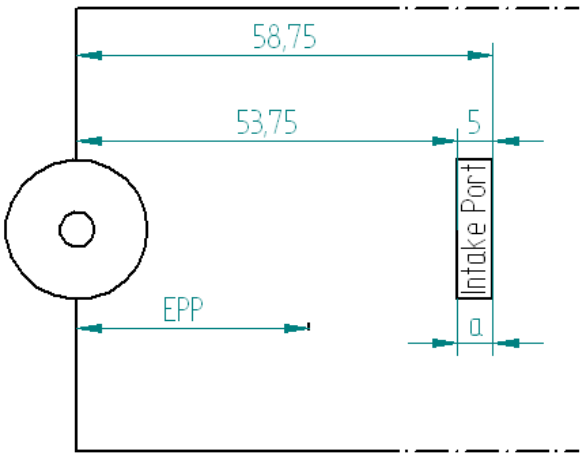


Figure 51: Measurements of intake side.

if EPP = or > 53,75 then a = 58,75 – EPP
if EPP < 53,75 then a = 5
if EPP = or > 58,75 then a = 0

Exhaust Total Surface Opened (ETSO):

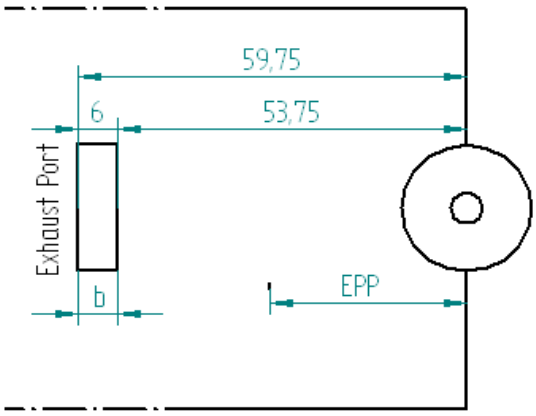


Figure 52: Measurements of exhaust side.

If EPP = or > 53,75 then b = 59,75 – EPP
If EPP < 53,75 then b = 6
If EPP = or > 59,75 then b = 0

Cylinder block pressure: P2 = (P1*V1^1,3)/(V2^1,3)

Configuration used:

Pistons 0,25 (18,75mm)
Phase difference 0deg
Delivered Ratio 60%

V2 = ∏*R^2*c = Variable, depending on c

Where c = 162,5 – EPP – IPP = variable, depending on crank angle.

It is necessary to add 0,094 cm^3 to V2 in concept of spark plug and pressure sensor cavities.

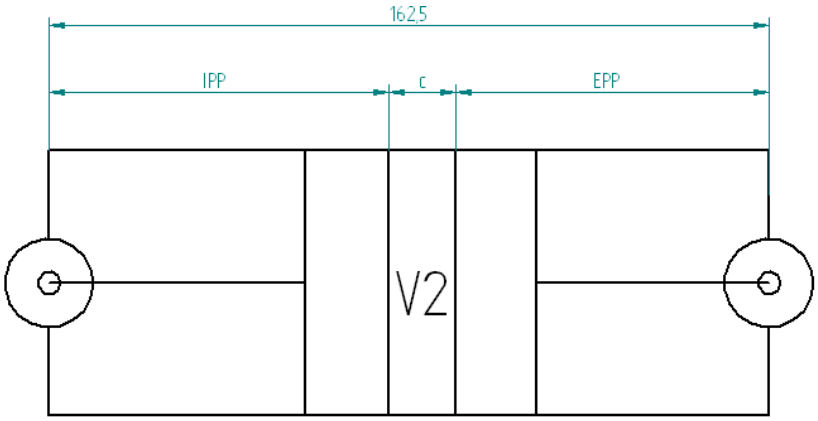


Figure 53: Engine in TDC.

V1 = ∏*R^2*d = 37,390 cm3
d = depending on pistons height and Phase difference, using the crank angle where P1 is taken P1 (manual calculation).

It is necessary to add 0,094 cm^3 to V2 in concept of spark plug and pressure sensor cavities.

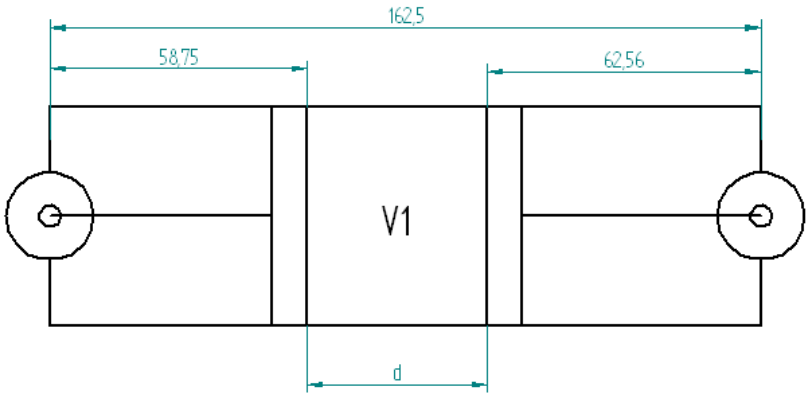


Figure 54: Engine at the moment of taking the value for V1.

$$V1 = 12{,}235\ cm^3$$

But as is said before P1 is not calculated, it is obtained from the program by looking for a crank angle when both ports are closed. Then find P1 on the graph and finally calculate V2 at that point. But this is only theoretically, because the ignition and the amount of fuel are not considered.

As example:

- Exhaust: At -161deg for 0deg of Phase difference and 0,25 of piston height, the exhaust port starts to close. In this point the pressure will start increasing, and then it is necessary to use the program to find the pressure in one moment after that. This pressure will be considered as the initial pressure of the engine. Mention again that this pressure is only valid for that combination of pistons, Phase difference and delivered ratio of the air pump.

  At -113 deg the exhaust port is full closed.

- Intake: At -166 deg starts to close.

  At -119 deg is full closed.

Compression Ratio: the useful *cr* shows us the highest Compression Ratio.

cr = V1/V2

Other values:

By knowing the rpm of the engine it is possible to calculate piston's linear velocity, this added to the previous measurements make possible to know the time that each port is opened.

Piston height is given in values of 0 0,25 0,5 0,75 and 1, this is the distance that is being reduced from the pistons original surface (19mm). It's also necessary to know the distance between the bolt of the piston and the face of that.

Graphics*:

1. Port Opened Surface vs. Crank angle

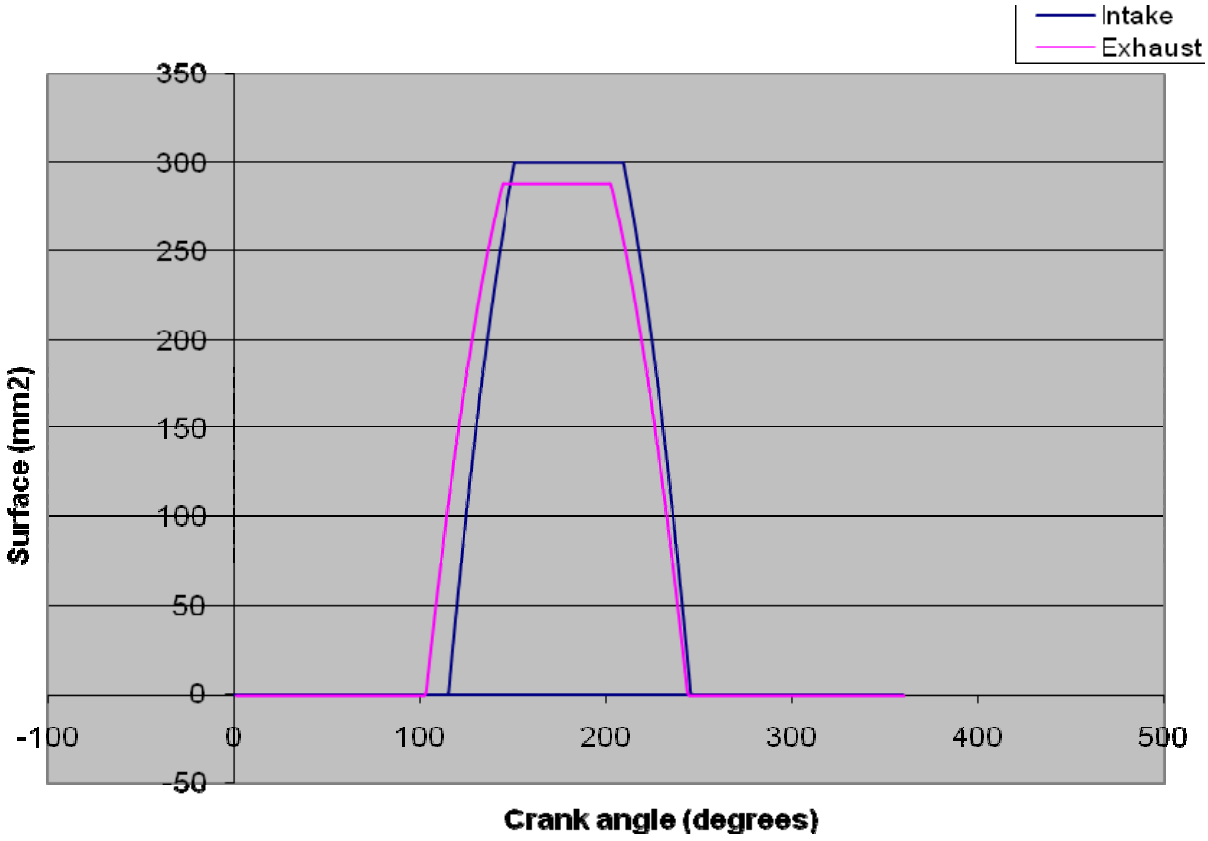


Figure 55: Port Opened Surface (mm2) vs. Crank angle (degrees)

It is possible to see how the exhaust port opens before and closes at the same time that the intake port. On the other hand, the intake port total surface is higher.

2. Total Volume 2 vs. Crank angle

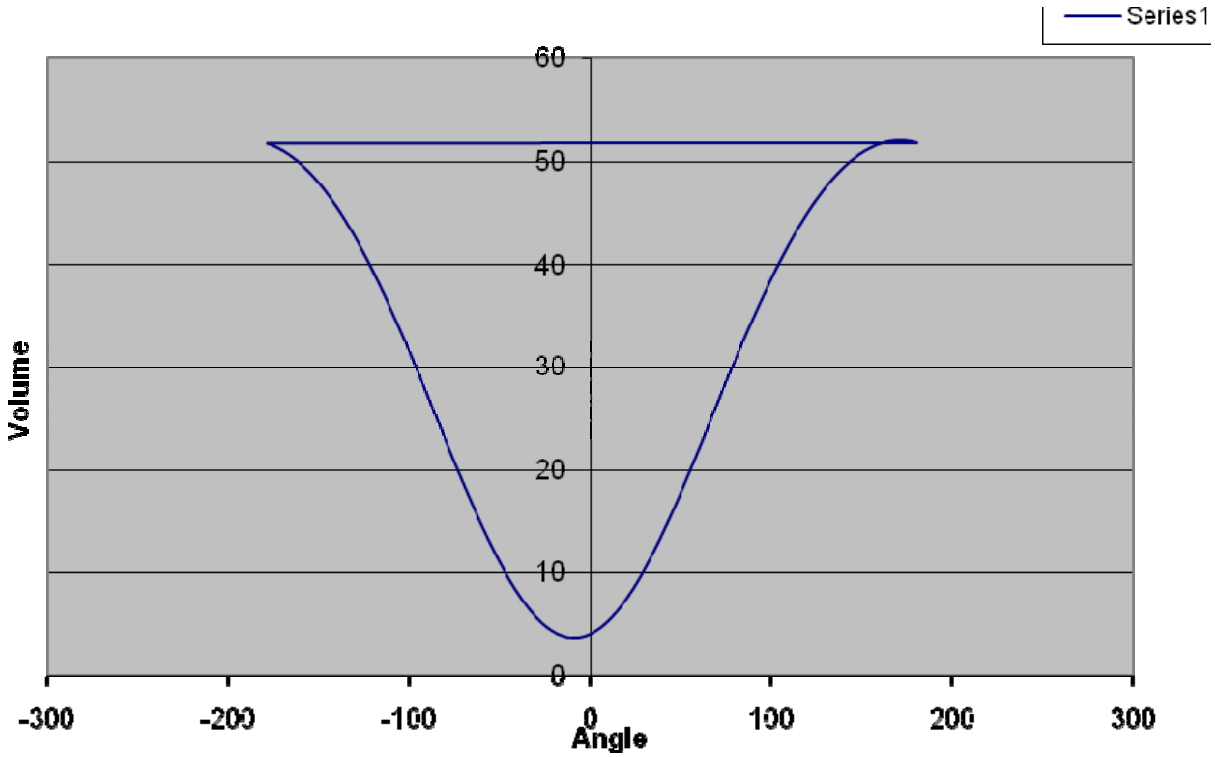


Figure 56: Total Volume 2 (cm3) vs. Crank angle (degrees)

Taking a cycle from -180º to 180º it is possible to see how the max volume is not in BDC, this is due to the phase difference.

3. Example of Compression Ratio vs. Phase difference (piston height 0,25)

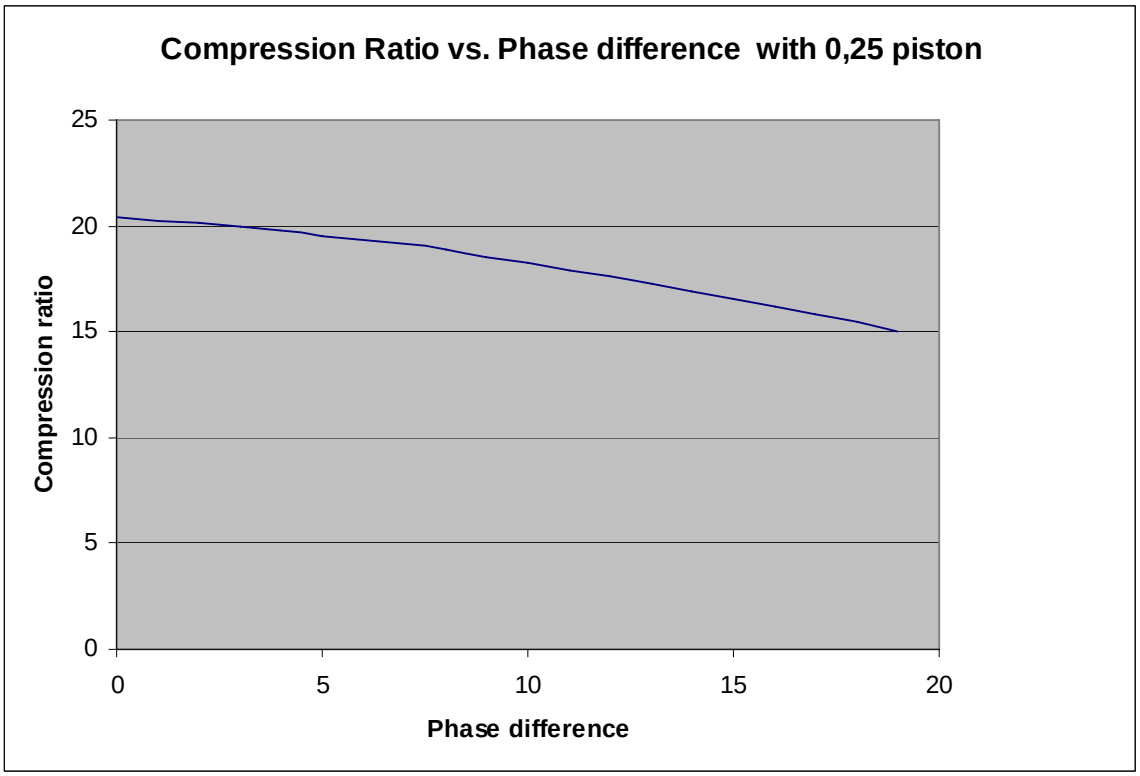


Figure 57: Max Compression Ratio vs. Phase difference

The file contains the graphs for each piston height. This graph shows how the max compression ratio changes in relation with the phase difference. Increasing the phase difference lowers the max compression ratio. This graph is for the performance used in the engine during the tests.

*Values for phase difference of 19 deg and piston height of 1.