The Study of a New Thermal Ignition Engine

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1. Introduction

Since last years, the whole world is moving towards a new direction. Sustainable energy is one of our priorities; trying to reduce pollutants as maximum as possible and avoiding the petrol dependency are some ways to achieve that. In this direction, engineers are working in electric cars, which have zero consumption. However, batteries still don’t have sufficient autonomy such as an internal combustion car. Furthermore, when you are running out of batteries, the recharge time is too much compared to the 5 minutes that takes to fill a tank. In a few years this could be solved, but before that occurs, some engineers are researching other ways to consume less petrol and pollute less, putting emphasis on energy efficiency and use of renewable energy. This need for increased efficiency has placed the diesel engine in the spotlight due to its superior fuel efficiency compared to spark ignition engines. In this paper I will explain how we have been investigating a new kind of engine that runs with regular gas but using thermal ignition. Using the same principles as Diesel engines, it is possible to run an engine with regular gas but with a really lean mixture, reducing the pollutants and the consumption and gaining efficiency. And finally I will expose the obtained results and the conclusions.
2. Conventional engines

Efficiency
Compression ignition engine, commonly known as diesel engines, has a very high efficiency: around 40% versus 25% fuel efficiency on spark ignition engines. Although this evident advantage, they also have cons.

Pollutants
Diesel engines have more pollution problems that spark ignition engines. Regions of the combustion chamber pass through both rich and lean high temperature regions; that causes the formation of soot and NOx. Soot can be very harmful to people health so it is very important to reduce it. There are several ways to effectively reduce it. One of them is diesel particulate filter. However, it needs a periodic regeneration which increases fuel consumption. Also, as diesel engines normally operate lean of stoichiometric, there are no unburned hydrocarbons and CO to reduce NOx to nitrogen using a three way catalyst. It has been tried to run diesel engines at stoichiometric to achieve this but this leads to bad fuel economy. Finally, there are also forms of NOx after treatment that can be used with lean operation. The first one is lean NOx trap, which is like a three way catalyst reformulated to enhance storage of NOx during lean operation. NOx is reduced to nitrogen through reactions with products of rich combustion. That means that periodically this engine will have to run rich, thus fuel efficiency is also reduced. The second way to reduce NOx is selective catalytic reduction. With this technology it is possible to reduce NOx avoiding the need of running rich. Although using this system fuel efficiency won’t be reduced, selective catalytic reduction needs a reducing agent, which in this case is urea. This implies that vehicles need a second tank filled with urea. This reducing agent is injected in the exhaust system and NOx is reduced to nitrogen.

Conclusion
It seems clear that increasing fuel efficiency shouldn’t imply to use after treatment systems to reduce pollutants. That is why engineers have research new ways to increase fuel efficiency
without the need of these systems. In the next points I am going to explain a new way to achieve that: the Thermal Ignition Engine.
3. Thermal Ignition Engine

The resulting thermal ignition (TI) engine, also known as homogeneous charge compression ignition (HCCI) engine, is fundamentally different from the spark ignition (SI) and the compression ignition (CI) engines, also known as Diesel engines. In the Thermal Ignition engines the combustion initiation depends on kinetically driven oxidation process that does not rely on flame propagation. The Thermal Ignition engines have high fuel efficiency due to unthrottled operation and rapid heat release and low emissions of nitrogen oxides due to the low peak cylinder temperatures. Lean mixtures (Air Flow Ratio = 20) allow operation with conventional catalytic converters for reduction of hydrocarbons and other emissions through exhaust after treatment.

As in homogeneous charge spark ignition, the fuel and oxidizer are mixed together. However, rather than using an electric discharge to ignite a portion of the mixture, the density and temperature of the mixture are raised by compression until the entire mixture reacts spontaneously. Stratified charge compression ignition also relies on temperature and density increase resulting from compression.

The defining characteristic of Thermal Ignition is that the ignition occurs at several places at a time which makes the fuel/air mixture burn nearly simultaneously. There is no direct initiator of combustion. This makes the process inherently challenging to control. However, with advances in microprocessors and a physical understanding of the ignition process, Thermal Ignition engines can be controlled to achieve the emissions that would have a gasoline engine along with the efficiency of a diesel engine. In fact, HCCI engines have been shown to achieve extremely low levels of Nitrogen oxide emissions (NOx) without an aftertreatment catalytic converter. The unburned hydrocarbon and carbon monoxide emissions are still high (due to lower peak temperatures), as in gasoline engines, and must still be treated to meet automotive emission regulations.

Recent research has shown that the use of two fuels with different reactivities (such as gasoline and diesel) can help solve some of the difficulties of controlling HCCI ignition and burn rates. RCCI or Reactivity Controlled Compression Ignition has been demonstrated to provide highly efficient, low emissions operation over wide load and speed ranges.
Once ignited, combustion occurs very quickly. When auto-ignition occurs too early or with too much chemical energy, combustion is too fast and high in-cylinder pressures can destroy an engine. For this reason, HCCI is typically operated at lean overall fuel mixtures.

Advantages

- HCCI provides up to a 30 percent fuel savings, while meeting current emissions standards.
- Since HCCI engines are fuel-lean, they can operate at Diesel-like compression ratios, bigger than 15, thus achieving higher efficiencies than conventional spark-ignited gasoline engines.
- Homogeneous mixing of fuel and air leads to cleaner combustion and lower emissions. Actually, because peak temperatures are significantly lower than in typical spark ignited engines, NO\textsubscript{X} levels are almost negligible. Additionally, the premixed lean mixture does not produce soot.
- In regards to gasoline engines, the omission of throttle losses improves HCCI efficiency.

Disadvantages

- High in-cylinder peak pressures may cause damage to the engine.
- High heat release and pressure rise rates contribute to engine wear.
- The autoignition event is difficult to control, unlike the ignition event in spark ignition (SI) and diesel engines which are controlled by spark plugs and in-cylinder fuel injectors, respectively.
- HCCI engines have a small power range, constrained at low loads by lean flammability limits and high loads by in-cylinder pressure restrictions.
- Carbon monoxide (CO) and hydrocarbon (HC) pre-catalyst emissions are higher than a typical spark ignition engine, caused by incomplete oxidation (due to the rapid combustion event and low in-cylinder temperatures) and trapped crevice gases, respectively.
4. Research Project

Our goal is to apply a new technique of Thermal Ignition engine, simpler and cheaper than the ones that are being investigated nowadays. Our research project starts with the study of a 4 stroke engine, which in the point below is going to be explained with more detail. First step consisted on disassembling all the engine parts, to check they were in good shape and that they were within the correct tolerances. Next step was changing the crankshaft; this was done because the original crankshaft had a conical fit and it was needed one with a keyed end.
After all this, the engine was reassembled and the valve clearance was set up. A new frame was designed and welded and the engine was mounted on an engine test bench.

Then, the water brake dynamometer is coupled into the engine crankshaft and all the wires are connected. Now, it is possible to monitor the rpm of the engine, the torque and the horse power.

Next step is the carburetor. In this case, is has been used a motorbike Mikuni carburetor, which is easy to make the set up of the main jet and the needle. We started with a 100 main jet and the needle in the medium position. To mount the carburetor on the engine, we had to machine an adaptor. We made it with aluminum, using the lathe and the mill.
Next, a long throttle cable was bought, around 50 inches, and connected to the carburetor. The other side of the cable had to be tied to a throttle lever. For this task, another aluminum piece had to be machined. It was made a pulley so the cable could move back and forth very smoothly. Finally, the engine was ready to run for the first time.

After running the engine for some time, it was time to connect the gas emission analyzer. This had to be connected to the exhaust so it could analyze the gasses, and this made possible to know if the engine was running lean, rich or stoichiometric. First of all, the machine needed some maintenance due to the long period of time it hadn’t been used. The O₂ sensor was replaced and a four component gas was ordered in order to calibrate the machine, doing a single point calibration.
Although the machine was now ready to work, first we needed to assemble the water brake dynamometer to the engine, so this way we could manage to add different charges to the engine. For this purpose, the hoses had to be properly connected, and the interface console programmed. It was now when it was possible to run the engine and set the carburetor to adjust the air fuel ratio in all the revolutions per minute range. A lot of time was needed to achieve this and finally it was possible to maintain the air fuel ratio close to 14.7, the stoichiometric point.

Next, once all was ready, emission data, torque and horsepower were measured at different charges and revolutions. With this, it was possible to create a 3d map of the engine (torque, rpm and charge) and a chart with the emissions at this different studied function points. This was a lot of work and hours and a great achievement since this was tried for several years and it hadn’t been possible to get this data.

Next, the thermodynamic cycle was needed in order to now the efficiency of this engine and be able to compare it to the thermal ignition engine. For this task, it was needed to measure the pressure inside the combustion chamber; this was done with a pressure transducer. The cylinder
head was modified and one hole was drilled and threaded from the outside to the inside of the cylinder head.

This transducer was connected to an amplifier, then to a National Instruments Interface and finally to the computer. With Labview it was possible to record the data very fast and accurately. Obviously, now it was needed to be able to record the crankshaft position with an encoder which needed to be really fast. For this task, three different encoders were tried till finally it was found one that met the expectations. A new and powerful Digital interface was also needed. Apart from that, a custom support was made with CNC machining. First was designed with Solid Works and then made with a CNC mill.
This had to be really solid and perfectly aligned so the encoder didn’t break due to it ease to break due to high and fast vibrations.
Although it doesn’t seem to be this way, the hardest part of all that wasn’t this, it was programming Labview with two different interfaces and be able to record crankshaft position and pressure inside the combustion chamber at the same time and synchronized. After several days, finally it was possible to achieve that.

So, finally the final setup was done and it was possible to start acquiring data. The throttle had ten different positions, so it was held in a position and a rpm swept was done. This procedure was repeated with every throttle position. This was done to obtain the torque and horsepower curves. Next, for each throttle position, different engine speeds were held during several minutes, till the emissions were stabilized and then were measured. Now, the emission data in different engine working points was also acquired. Finally, the most important and difficult task was done: this was the Thermodynamic Cycle. It was needed a lot of attempts till it finally was possible to get it.

Till here was the first part of the research project. Now it was meant to modify the cylinder head to be able to put a ceramic piece into the combustion chamber. This had to have a channel where the fuel air mixture could go through causing the combustion initiation. This part was critical because only to cylinder heads were available; that meant one for the standard engine and the other for the modified engine, there wasn’t a chance to ruin it. Using the mill carefully it was possible to attain it.
Although a good job was done, the piece was too fragile so it didn’t hold in place and there was a high risk of the piece falling into the cylinder, ruining the engine. Then a great idea came up: Creating a secondary combustion chamber that would be connected to the principal combustion chamber through the spark plug hole in the cylinder head. Another change was meant to be applied: Instead of a ceramic piece, it was wanted to use a glow plug inside the secondary combustion chamber. The designs and plans were done with Solid Works and the piece was made using a CNC mill.

Although it seemed a great idea, the glow plug used for this test was one that was used in diesel engines and it was only designed to work for a few seconds, so after some minutes of working, it was spoiled.
Then, some more ideas were applied to this secondary chamber design. The first one was using Tungsten thread bent into circle as if it was a coil. Giving some Voltage we could turn it into glowing thread and this could work as a glowing plug, but with much more contact surface with the mixture. It was used Tungsten because its material properties, being able to put up with really high temperatures.
This didn’t work either, so finally it was decided to put a big ceramic piece into the secondary combustion chamber. This worked fine so we were ready to start recording data following the same procedures explained above.
5. Results

The obtained results are going to be presented and explained in this section. Since this is a big and long project, the data that has been obtained is very large; thus, only the most important results are going to be explained. To start with, the emission and consumption data are shown below.

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This data belongs to the engine without any modification, using the main jets that were found to work better. The consumption wasn’t bad at all, and the efficiency is very good. It is important to comment that each working point was measured using different main jets till the best configuration was found. The emissions are normal, considering we weren’t using a catalyst. It is also interesting that it was managed to be really close to the stoichiometric point (AFR = 14.7), and if it was possible, in the lean side.
Once we had the consumption and the emissions data, the next thing it was done was measuring the horsepower in different rpm speeds and different throttle positions.

First of all, it can be seen that at high throttle rates, the rpm speed was always higher than 3000 rpm, that is because since the engine has a single cylinder, it was really irregular and unstable at such speeds; however, at higher speeds it ran perfectly. Another interesting point is that the higher power was always around 3200-3600 rpm, this is because the engine was designed to have the highest amount of torque at 3600 rpm, since this engine was designed to work as an electric generator and it needed to run at 60Hz.
This is the thermodynamic cycle of the engine running at 4200 rpm and the throttle in the 80% position. This is the first time that it was possible to measure the thermodynamic cycle of this engine in our lab. The pressure is relative and doesn't have units; this is because the used transducer worked this way. However, it was still a great success, considering all the troubles that were found to achieve that. It can easily be distinguished the two separate parts: the intake zone, which is the part from the bottom, where the pressure is the lowest, and the compression, ignition and exhaust zone.

Now, what it would be really interesting is to compare this thermodynamic cycle with the one from the thermal ignition engine. However, due to the short time to do this whole project,
less than one year, it hasn’t been possible to refine the operation of this engine. The obtained cycle couldn’t be at the best set up of the engine. Surely, with more time and effort this cycle would improve greatly. This is the cycle we could obtain.

Also a good one but not as good as expected. It would be necessary more time to keep improving the setup of the engine.
6. Conclusions

After a long year of working in this project, a lot of improvements and discoveries have been done. In the previous point, the results have been presented and it is obvious that it still needs more time, data and work on it to be able to develop this promising technique. What it is more interesting is that although this engine is not completely developed, the obtained results are really optimistic and encourage keeping investigating in this direction. Only being able to make the ceramic peace work as a thermal ignition source without causing the knocking effect is an amazing feat.

If this technique could be developed even more, it could be really easy a cheap to produce this engines, being able to run on lean mixtures, consuming less fuel, achieving higher efficiencies and what is more important, polluting less.

Time will tell if this will be the next generation of high efficiency and low pollutants engines, but one thing is clear, HCCI engines are the most promising technology in terms of specs and also in terms of easy adaptation to the society.
7. References


