Methods To Improve Thermal Efficiency Of A 4-S Petrol Engine

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Abstract: This thesis describes the work of developing a technology demonstrating single cylinder engine. The engine was to display five different technologies that could be of use in the continued development of their fuel efficient engine.

The first technology investigated was the use of ceramics and low-friction materials in the combustion chamber in order to reduce heat and friction losses and hence increase the thermal efficiency.

Using the ideal thermodynamic Atkinson cycle was the second technology investigated as it has a higher thermal efficiency than a conventional Otto cycle engine and can be utilized by relatively small mechanical changes of the existing engine.

Replacing the conventional electric spark plug with a laser ignition system to achieve a more efficient combustion and lower the engine heat losses were investigated as a third fuel efficient technology.

Direct injection was investigated as a fifth technology and a possibly more fuel efficient method of fuel injection, specifically the air assisted direct injection system.

With the implementation of the above mentioned techniques one can certainly expect to have an increased efficiency overall and not just thermal efficiency. Some of the other new techniques viz. water injection and LHRE engines have also been used and looked into.

Introduction

1.1 Overview

The walls enclosing the combustion chamber is normally made out of metal materials. Metals are easy to process and can resist the mechanical stresses occurring in an engine. However, metals are good heat conductors. They will thereby transfer a lot of heat energy away from the combustion chamber. This is known as in cylinder heat losses. Ceramic materials have extremely low heat conductivity. This method was therefore chosen focusing on implementing ceramic materials in the combustion chamber to insulate the combustion chamber and hence lower the in cylinder heat losses.

In the 21st century, energy saving and environmental protection have become an important development strategy in the world. It is generally known that transportation sector is a big consumer of energy. There are more than a billion cars in the world. With such a large number of cars, not only large amounts of energy is consumed but also a lot of harmful gasses is sent in to the environment. For this reason many countries are introducing more stringent vehicle fuel economy and emission standards.to save energy. IC engines plays a very important role in energy saving and environmental protection. Therefore, automakers and researchers have made a lot of effort to improve fuel efficiency and emission level of IC engines.

This section describes the theory behind laser ignition, and the possibilities to implement it in the technology demonstrator. Conventional spark-ignited (SI) engines utilizes spark plugs to ignite the fuel mixture. Spark ignition has been used since the invention of internal combustion engines but modern spark plugs still affect combustion performance adversely. Because of their location inside the combustion chamber, spark plugs absorbs a lot of heat from the combustion process.

Direct injection is a method of fuel injection which in this section is evaluated with regards to overall engine performance. The theory behind direct injection is described and the design chosen for the implementation in the technical demonstrator is described and motivated. The results are then presented and analysed.

Water injection is relatively a very new technology in the automotive sector. The major drawback of using lean mixture with direct injection is that there will be high amount of NOx produced and the power and torque figures will be significantly lower, thus reducing the overall performance. Hence, water injection was introduced. Though the name suggests “water injection”, it’s not exactly pure H2O that is supplied. It is actually a 50-50 mixture of methanol and water.

OBJECTIVES

The main objective was to improve the efficiency of the existing 4-S SI engine using various methods and to provide a meaningful comparison between the original and the modified setup. The aim in the end is to increase the thermal efficiency by introducing various existing and new technologies to obtain an output that could be put in use in the existing engines and at the same time reduce the pollution and emission as an added advantage. Few of the technologies discussed, had already been developed and few have been started as a field for fresh research. The methods or technologies were individually tested out in the engine separately. The results before and after the implementation of the particular technology was studied and shown. In a few cases the dealer dealing in the certain areas was also contacted and asked for help. A system was devised and further results were checked out in CAD or in actual engine.

CHAPTER 3

Ceramic Materials Coating In Lhre

Introduction

The walls enclosing the combustion chamber is normally made out of metal materials. Metals are easy to process and can resist the mechanical stresses occurring in an engine. However, metals are good heat conductors. They will thereby transfer a lot of heat energy away from the combustion chamber. This is known as in cylinder heat losses. Ceramic materials have extremely low heat conductivity. This method was therefore chosen focusing on implementing ceramic materials in the combustion chamber to insulate the combustion chamber and hence lower the in cylinder heat losses.

Theory

A great amount of heat energy is released when the air-fuel mixture is combusted in the combustion chamber. This energy increases the temperature of the gases which will heat up the surrounding surfaces in the combustion chamber. The surfaces transfers some of the heat energy away which results in heat losses. A higher heat conductivity of the wall materials lead to higher heat transfer and thereby more heat losses. A material with low heat conductivity is thus desired. The released energy of the fuel can be divided into three parts: heat transfer and friction losses, mechanical work and energy in the exhaust gases. The principle of using ceramic materials, with low heat conductivity, was to insulate the combustion chamber and minimize the heat transfer losses and instead gain more mechanical work from the same amount of fuel.

To contain as much heat energy as possible in the gases of the combustion chamber an insulating thermal barrier between the combustion chamber and the engine block is needed. This barrier had to be made out of a material which could withstand the thermal and mechanical stresses and have a low heat transfer conductive coefficient. Ceramics have these properties and is therefore the material type used in such thermal barriers. The surfaces which are enclosing the combustion chamber are the piston crown, the cylinder liner and the cylinder head.

These surfaces could either have inserts, or whole parts, made out of ceramics or regular metal parts with a ceramic coating to make the thermal barrier. The use of coated surfaces is the simplest and most common way to create a thermal barrier. These coatings are called Thermal Barrier Coating (TBC) and are commonly used in gas turbines. The turbine blades are coated with a TBC to withstand higher temperatures and to lower the heat transfer into the material of the blade. The same concept could be used in internal combustion engines to minimize the heat losses.

Engines using thermal barriers, either with coatings or inserts, have combustion chamber surfaces which are only rejecting a small amount of heat and are therefore known as Low Heat Rejection Engines (LHRE). These engines only exist as research test engines at the moment, but are expected to improve the fuel efficiency in conventional internal combustion engines as well as to eliminate the need for engine block cooling.

Advantages

Ceramics have many desirable properties for usage in the combustion chamber. They are resistant to high temperatures and are chemically stable. In addition, technical ceramics are resistant to wear and can withstand high compressive stresses with a desired low heat conductive coefficient. This is why technical ceramics are being used for creating thermal barriers. Many investigations has been carried out on LHRE and the results are inconsistent. This has led to other reports comparing the investigations to find out why their results differ.

However, some investigations suggest that LHRE instead decreases the performance, due to increased losses. These losses are explained as increased friction due to lack of lubrication between piston rings and cylinder liner at higher temperatures.

Another explanation why LHRE are less efficient in some test was the decreased volumetric efficiency (VE) due to increased temperatures of the combustion chamber walls. If the walls have a higher temperature when new cold gases are inhaled through the intake valve, the gases will heat up and therefore expand more. When the gases expand, less air and less oxygen molecules will be inhaled into the combustion chamber, which decreases the VE.

But the investigations also confirms that the thermal efficiency was increased with the use of LHRE. The thermal efficiency explains how much of the heat energy in the fuel that is converted to mechanical work. This leads to a trade-off between the volumetric and thermal efficiency, but when LHRE was compared with conventional engines at the same AFR the LHREs showed decreased fuel consumption. This way of comparing the engines was regarded to be the fairest comparison as the combustion properties would be equal.

Problems

The research of today on LHRE is mainly focusing on implementing ceramic materials in diesel engines. Diesel engines are compression ignited and the increment in temperature due to ceramic surfaces in the combustion chamber only effects the combustion process in a positive manner.

This project, on the other hand was focusing on implementing ceramic materials in a small petrol engine. A petrol engine is spark ignited, where an increment in temperature can result in spark knock. Spark knock occurs when small pockets of combustion gases self-ignites at the edge of the combustion chamber, which have a destructive effect on the engine. The compression ratio is often lowered to avoid knock. Implementation of ceramic material in a spark ignited engine can therefore lead to the need of lowering the compression ratio, which reduces the thermal efficiency. The benefit of ceramic materials in spark ignited engines is hence less straightforward compared to compression ignited engines.

This makes a small engine less fuel efficient compared to larger engines, since the displacement volume determines the possible heat energy release from the fuel and a larger surface area gives higher heat transfer losses. This explains the reason why implementation of ceramics in large spark ignited engines is considered inefficient. However, this project is aiming to implement ceramics in a small engine which runs for a short period of time and this makes the implementation of ceramics interesting with a potential of increasing the fuel efficiency.

If the cylinder liner is chosen to be made in ceramics another issue with the mating material in the piston rings occurs. The hardness ratio between the materials in the cylinder liner and the piston rings is matched to minimize wear on the piston rings and still keep the friction as low as possible. The material in the piston rings has to be increased a lot if the same ratio is used with the much harder cylinder liner in ceramics.

Material:	**Melting temp.: [K]**	**Conductive heat coefficient: [W/mK]**	**Elasticity module:** [**GPa**]	**Fracture toughness:** [**Mpa**1/2]	**Hardness: [HV]**
Al2O3	2050	16	230-260	4.5	1400
ZrO_2	2700	1.7	170-200	4	1200
SiC	300	62.0	390-410	3.4	2800
TiO_2	1850	5.2	275-290	2.7	980

Material Properties

A ceramic material consists of a metal and a non-metal, like alumina (Al_2O_3). The use of ceramics in internal combustion engines is well known and tested in the research society. Table 1 shows the properties of some technical ceramics. Interesting properties when choosing materials for LHRE are primarily conductive heat coefficient, melting temperature and fracture toughness.

The first ceramics to be used in LHRE were alumina (Al_20_3) and silicon carbide (SiC) since these are well known and accessible. Other ceramics such as zirconia (ZrO_2) and titanium oxide (TiO_2) was soon adapted in the research engines. Zirconia and titanium oxide both have low heat conductive coefficient and high melting temperature, this is preferable for usage in LHRE. However zirconia has higher fracture toughness and lower conductive heat coefficient than titanium oxide, two properties very crucial in a LHRE.

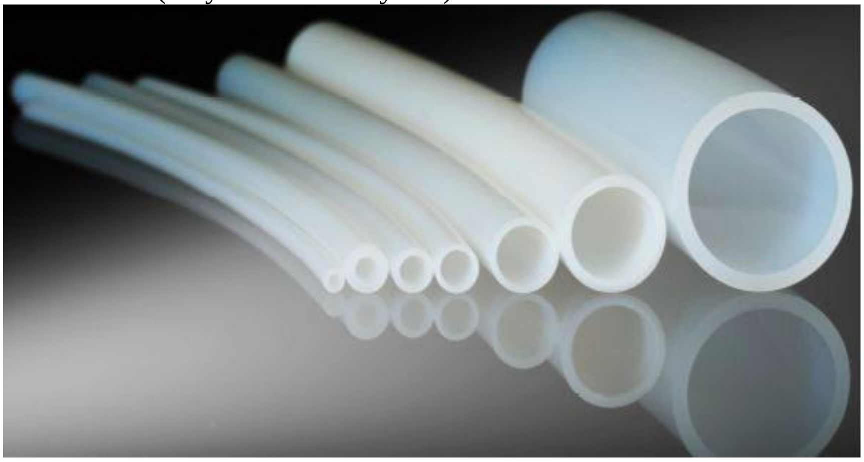
Solid Parts or Coatings?

Solid parts and coatings have different pros and cons. Coatings are generally easier to implement since they can seize the mechanical structure of the metal part. A coating is on the other hand much thinner than the thickness of a part made of solid ceramics. The conductive heat resistance depends on the thickness of the thermal barrier. A solid part in ceramics will thereby have a greater thermal resistance which decreases the heat losses more than a coating would.

Low-Friction

The friction in the piston ring-piston liner system stands for approximately 40 % of all mechanical losses in the propulsion system, which relates to 5-10 % of the fuel consumption. A decrement in piston ring friction will therefore improve the efficiency of the engine.

The project aimed to find several solutions which decreased the piston ring friction and still made the other engine improvements possible. One option was to use low-friction rings made out of PTFE (Polytetrafluoroethylene).



PTFE Teflon tubes

Low-friction rings made out of PTFE (Polytetrafluoroethylene) has the lowest friction coefficient. In addition a self-lubricating piston ring is not in need for lubrication by oil which enables the use of an open crankcase. An open crankcase would decrease the pumping losses which occurs when a pressure builds and air is pumped in and out the oil trap up as the piston moves up and down.

The drawbacks with PTFE is that it cannot withstand higher temperatures than 250˚C. On a large diesel LHRE, the upper piston ring can reach temperatures of up to 550°C[13]. But, as mentioned earlier, the CVT engine is colder than usual diesel LHRE engines and the aim was therefore to still test these PTFE piston rings.

Piston Crown and Cylinder

The areas that were selected to be coated with a thermal barrier layer is the parts that are included in the combustion chamber. These are the surfaces of the valves, cylinder head, the piston head and the cylinder liner wall. The thermal barrier layer and its thickness that is used here is the same as for the cylinder liner.

Piston Rings

The difficulty in having a hard cylinder liner in zirconia and still keep the friction and the wear on the piston rings as low as possible, lead to the decision that several designs of the piston rings should be tested. The PTFE piston rings with the lowest friction coefficient had the greatest possibility to minimize the friction losses. But, they did not have the specified properties to withstand the high temperature in the combustion chamber. Although tests were still considered useful to conduct to see what effect these piston rings would have on friction losses.

Due to the uncertainty of the reliability of the PTFE ring, conventional piston rings were the most realistic choice. The possible risk with these could be higher friction and substantially more wear on the piston rings

CHAPTER 4

Converting Work Cycle From Otto To Atkinson

Introduction

In the 21st century, energy saving and environmental protection have become an important development strategy in the world. It is generally known that transportation sector is a big consumer of energy. There are more than a billion cars in the world. With such a large number of cars, not only large amounts of energy is consumed but also a lot of harmful gasses is sent in to the environment. For this reason many countries are introducing more stringent vehicle fuel economy and emission standards.to save energy. IC engines plays a very important role in energy saving and environmental protection. Therefore, automakers and researchers have made a lot of effort to improve fuel efficiency and emission level of IC engines.

Since most of the time gasoline engines are part load operated in vehicle applications, especially in city traffic, part load operation covers most common operation situations. However, engine part load performances have been deteriorated due to pumping losses and low thermal efficiency. There are many methods to improve engine thermal efficiency, such as low friction, boosting, variable valve timing(VVT), variable valve lift(VVL), new combustion mode and Atkinson/miller cycle. At present the most fuel efficient cars have adopted Atkinson cycle engine ass the main power.

Theory

Atkinson cycle is a novel IC engine cycle which was invented by James Atkinson in 1882. The main difference compared to Otto cycle is that its compression stroke is shorter than its expansion stroke through a multi-link crankshaft system in the original state and modern embodiment of Atkinson cycle uses LIVC via valve methods instead of the multi-link crankshaft geometry. Atkinson cycle delivers more energy from the combusted gas to the piston during over expansion process than that of Otto cycle. Thus, the Atkinson cycle engine is more effective than a conventional Otto cycle engine.

However, the effective CR of Atkinson cycle is reduced due to LIVC. At the initial stage of compression stroke, some of the air that has entered into the cylinder is returned to intake manifold. In this situation, effective displacement of over expanded cycle is reduced, power density decreases and combustion performance deteriorates compared to Otto cycle due to decreasing of effective CR. That will mean that the maximum power and torque of Atkinson cycle engine are lower than those of Otto cycle engine.

Many investigations have been done upon Atkinson cycle due to its advantages by several research groups. In the year 2008, yasin conducted a comparative performance analysis and optimisation of Atkinson cycle under maximum power density (MPD). The results showed that for the Atkinson cycle, a design based on the MPD conditions is more advantageous from the point of view of engine sizes and thermal efficiency.

Taylor et al. investigated the effects pf Atkinson cycle applied to a 1.4 litre gasoline direct injection turbocharged engine. He used asymmetric intake valve timing control to effectively provide a method of running increased intake cam duration allowing LIVC cycle strategies to be adopted. The results demonstrated high load combustion phasing improvements through reduced effective CR and improvements at part load through pumping work reduction.

item	Original conditions	Targets
	Otto cycle engine	Atkinson cycle engine
Max power	75 KW/6000rpm	60KW/5200rpm
Max torque	136N.m/4000rpm	130N.m/4000rpm
Min BSFC	255 g/KWh	235 g/KWh

Applications of LIVC operation has been evaluated overdrive cycle. In one of the research it was found that LIVC operation combined with a variable compression ratio (VCR) device could improve over cycle fuel consumption by 13%. Many other research shows that Atkinson cycle combined with a high CR played a major role while optimizing, friction reduction played a secondary major role in engine thermal efficiency improvement.

The original Otto cycle engine, which is taken as example in this paper is a 1.58 litre, 4-cylinder, four stroke, 4-valve, water cooling, naturally aspirated engine with CR of 10.5the specifications is listed below.

In order to decrease the fuel consumption, the original Otto cycle should be modified into Atkinson cycle engines. Some parameters of the engine cannot be changed like the bore, stroke, displacement and crankshaft structure with the purpose of time and cost saving. The comparison of technical parameters between original Otto cycle and Atkinson cycle engine are shown below.

Engine Modification and Optimization

In order to achieve the objectives shown in the table above, some measures will be taken, such as increase in compression ratio, optimize piston shape, optimize CAM profile, AFR, valve timing and ignition timing optimization. These modifications are attained without involving a complex mechanical structure and enlarged engine size, and at the same time without any large modifications being made to the original Otto cycle engine.

Compression ratio theoretical calculations

According to the table above the optimal compression ratio for an Atkinson cycle can be calculated by the following method.

The volume power of original Otto cycle engine is:

$$PL = \frac{Pe}{iVs} = \frac{75}{1.485} = 50.5$$

Where PL is volume power, KW/L; Pe is the maximum power, KW; I is the number of cylinders, Vs is the single cylinder volume, L

$$Vs = \frac{1.485}{i} = \frac{1.485}{4} = 0.371$$

The compression ratio of original Otto cycle engine is:

$$\varepsilon 0 = \frac{Vs + Voc}{Voc}$$

$$Voc = \frac{Vs}{\varepsilon 0 - 1} = \frac{0.371}{10.5 - 1} = 0.039$$

Where ε0 is the CR of original Otto cycle engine, Voc is the clearance volume of original Otto cycle engine.

If the volume power of Atkinson cycle engine is the same as that of the original Otto cycle engine, the effective working volume of single cylinder of Atkinson cycle engine is:

$$iVs' = \frac{Pe'}{PL}$$

$$Vs' = \frac{Pe'}{iPL} = \frac{60}{4 \times 50.5} = 0.297$$

Where Pe' is the maximum power of Atkinson cycle engine, KW, Vs' is the effective working volume of the single cylinder of Atkinson cycle engine, L.

In order to avoid the occurrence of knocking, the theoretical effective CR of the Atkinson cycle engine keeps the same as original Otto cycle engine. So the clearance volume of Atkinson cycle engine is:

$$\varepsilon ae = \frac{Vs' + Vac'}{Vac'}$$

$$Vac' = \frac{Vs'}{\varepsilon ae - 1} = \frac{0.297}{10.5 - 1} = 0.0312$$

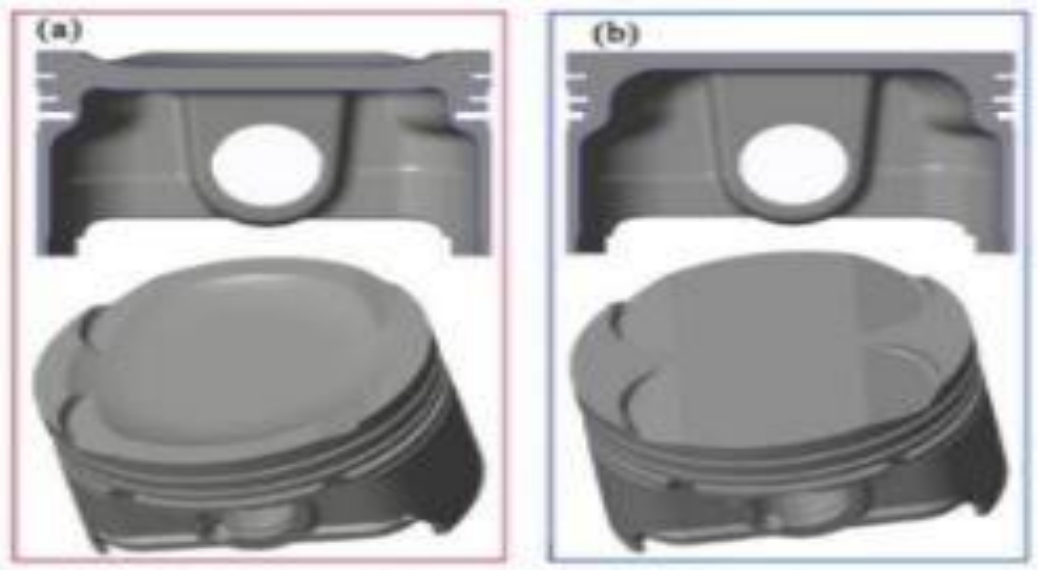
Where εae is the effective CR of Atkinson cycle engine, Vac' is the clearance volume of Atkinson cycle engine, L

So CR of Atkinson cycle engine is:

$$\varepsilon ag = \frac{Vs + Vac'}{Vac'} = \frac{0.371 + 0.0312}{0.0312} = 12.9$$

Where εag is the CR of Atkinson cycle engine. Therefore CR of Atkinson cycle engine ca be set up as 13 and the clearance volume is set as 0.0312.

Piston Modifications



Since it is studied that piston shape has some effects on air turbulence, the effects of different piston designs were researched upon, and this design was finalised.

Cam Profile Optimization

Atkinson cycle engine uses LIVC to reduce pumping losses, so the CAM profile should be optimised. First of all, the intake advanced angle will be reduced and the intake lag angle should be greatly increased to reduce the CR. That means increase the cam work angle. Then, both of exhaust advanced and lag angle should be reduced in order to delay the exhaust valve open timing and increase the actual expansion ratio.

Ignition Timing

Ignition timing has a significant effect on SI engines. It has a considerable influence on combustion characteristics, and therefore affects engine performance and combustion products. It is generally observed that too advanced ignition timing causes cylinder pressure to increase significantly and rapidly before the end of compression stroke. This increases the work lost in compression process, and therefore, decreases the net useful work. In contrast, too- delayed ignition timing results in a lower peak pressure occurring very late in expansion process. This reduces the work transfer from expanding gasses to piston. So there exists an optimal choice for ignition timing. The optimum ignition timing produces satisfactory high cylinder pressure, with its peak occurring just after top dead centre. This ensures minimum compression work and maximum work transfer during the expansion stroke.

From an overall perspective, with the load increasing, the ignition advance angle which before firing TDC decreased both for original Otto cycle and Atkinson cycle engine. Generally speaking, as engine speed increases, the ignition advance angle will increase at the same load.

Fuel Economy and Thermal Efficiency

Fuel consumption is an important indicator in engine evaluation. The main aim of this paper is improving engine fuel economy and thermal efficiency. With Atkinson cycle engine fuel economy is increased drastically as compared to conventional Otto cycle engine. This can be observed when a setup of Atkinson cycle is made and its performance is checked in a dynamometer. A decrease of around 16 g/KWh of fuel consumption is expected by the conversion of Otto cycle in to Atkinson cycle.

The thermal efficiency of Atkinson cycle engine is supposed to be much higher than that of original Otto cycle engine, especially at low medium speed. Also, the the high thermal efficiency region of Atkinson cycle engine is much wider than that of original Otto cycle engine.

CHAPTER 5

Replacing Conventional Spark System By Laser Ignition

Introduction

This section describes the theory behind laser ignition, and the possibilities to implement it in the technology demonstrator.

Theory

Conventional spark-ignited (SI) engines utilizes spark plugs to ignite the fuel mixture. Spark ignition has been used since the invention of internal combustion engines but modern spark plugs still affect combustion performance adversely. Because of their location inside the combustion chamber, spark plugs absorbs a lot of heat from the combustion process.

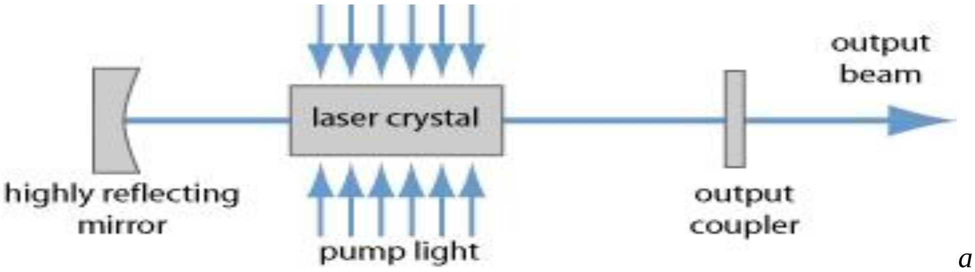
If the electrodes of the plug becomes too hot the engine may ignite prematurely. To avoid this, spark plugs are designed to transfer heat from the combustion chamber to the outside. This increases the heat losses in the engine and reduces thermal efficiency.

The electrodes that create the spark are also in the way of the flame during the initial part of the combustion stroke. The relatively cold surface of the electrodes may quench the flame during the early stage of ignition, causing a misfire. To counteract this, engines need to be operated on a richer (lower air-to-fuel ratio) fuel mixture than otherwise necessary. A too rich fuel mixture leads to less complete combustion and more fuel is wasted as it passes through the engine without burning.

A laser ignition (LI) system replaces the spark with a focused laser beam. The laser creates a small plasma inside the combustion chamber which ignites the fuel mixture. The system has been previously realised by placing the laser source apart from the engine and guiding the beam into the combustion chamber using mirrors and lenses. The beam typically enters the combustion chamber through a small, non-reflective window.

Basic Laser Theory

Figure below provides a very basic description of the operation of a laser. The highly reflecting mirror and the output coupler make up the boundaries of the laser system. The output coupler is a semi-reflective mirror through which some light can escape. During operation of the laser, light oscillates between these two mirrors. Light that escapes the output coupler becomes the actual output of the laser (the laser beam).

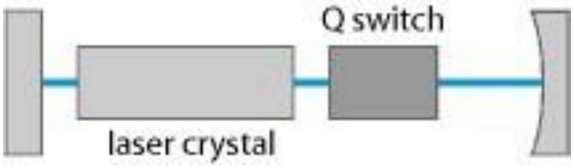


a sample model of a laser beam

The light oscillating inside the laser is amplified by a so-called gain medium. The gain medium can be a crystal as in this example, but may also consist of a gas (as in a CO2 or Helium-Neon laser) or a liquid solution (such as dye lasers). The gain medium in turn gets its energy from light sources located on the side. Common light sources are flash lamps and laser diodes. The process of energising the gain medium using other light sources is known as optical pumping.
Lasers can be divided into categories based on the type of gain medium used. Those lasers that use a solid gain medium such as crystals or glasses are known as solid-state lasers. Combining a solid-state gain medium with laser diodes as a pump light allows for a laser system that is compact, energy efficient and reliable. A diode-pumped solid-state (DPSS) laser would therefore be the optimal choice for use in vehicles.

Q-Switching

An optical resonator such as a laser may be described by its Q-factor. In terms of energy storage, the Q-factor describes the ratio of stored energy to dissipated energy in the resonator. The Q-switch is a device that allows for modulation of this factor during operation of the laser. The Q-switch is located inside the laser as seen in figure.



A model of a Q-switched laser

When resonator losses are kept at a high level (low Q-factor) no lasing (emission of laser light) can occur and most of the energy that is pumped into the gain medium stays there. The Q-switch can then create a sudden rise in Q-factor, corresponding to a drop in resonator losses. This in turn allows the resonator to charge up quickly and emit a strong pulse of laser light. Q-switched laser usually have pulses with a duration of a few nanoseconds.
There are several ways to construct a Q-switch, and the most important distinction is whether the switch is active or passive. Active Q-switches are triggered by an external controller while

passive Q-switches always pulse when the energy stored in the gain medium reaches a certain level. Active Q-switching allows for better control over parameters such as pulse energy, pulse duration and repetition rate, whereas in a passively Q-switched laser the output energy and pulse duration stays constant. The repetition rate of a passively Q-switched laser can be regulated by varying the intensity of the pump light.

Most experiments with laser ignition (LI) in engines have been carried out using actively Q-switched lasers. It is however possible that passive Q-switching may be sufficient, or even beneficial, for vehicle applications. There is usually no need to regulate pulse energy as long as it is high enough to ignite the fuel, and the relative simplicity of the passive Q-switch may be useful in reducing size and complexity of the system.

The Nd:Yag Laser

The neodymium-doped yttrium aluminium garnet (Nd:YAG) laser is one of the most versatile lasers in use today. It has commercial applications in various fields such as medicine, materials processing and military equipment. The name Nd:YAG refers to the laser crystal used as a gain medium. A major reason for its popularity is that the same crystal can be used in lasers with completely different characteristics. Nd:YAG lasers can be operated as continuous-wave (CW) or be pulsed with repetition rates ranging from a few Hz to hundreds of kHz. The Nd:YAG crystal can be optically pumped by either flash lamps or laser diodes depending on the application and the power required.

Improvements

LI offers several benefits compared to conventional ignition systems. The main reasons for improvement are the higher ignition power delivered by the laser, less heat transfer from the combustion chamber, and the absence of electrodes inside the combustion chamber.

Higher Ignition Power

Previous research conducted on LI engines has shown that the more intense pulse provided by an LI system compared to conventional SI makes it possible to ignite leaner fuel mixtures without risk of misfiring. Lean fuel mixtures (more air per unit of fuel) allow for a more complete combustion and thus better efficiency. One study reports that the lambda value of an LI engine could be increased from 1.0 to 1.1 without affecting engine stability and performance adversely. Others have achieved similar results.

Absence Of Electrodes

Removing the spark plug’s electrodes from the combustion chamber has benefits similar to the increase in ignition power. As described in the introduction to this chapter the electrodes may quench the flame and cause misfiring of the engine, especially when running with a lean mixture. This issue becomes more pronounced during cold starts.

Less Heat Transfer

One final benefit of laser ignition is the improved heat retention due to the lack of spark plugs. The issue with heat loss caused by spark plugs has also been mentioned in the introduction to this chapter. Good heat retention means less energy lost as waste heat, and one of the concepts evaluated in this project is a low heat rejection engine.

Due to the unconventional running characteristics of the engine good heat retention and cold start performance are important parameters. Since LI helps to improve both these parameters while also offering improved efficiency it was selected as a promising concept to be evaluated in this study.

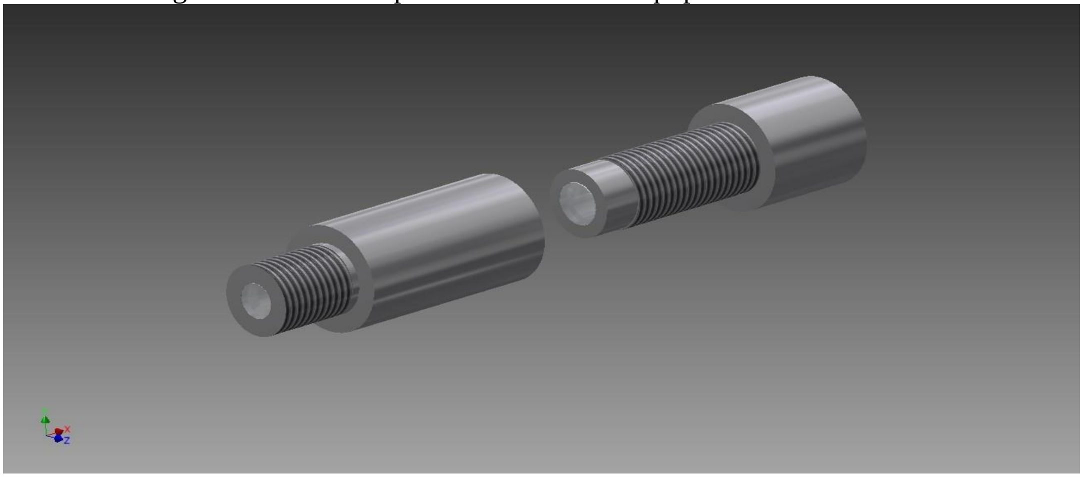
Drawbacks

The main issue with laser ignition systems today is the complexity and fragility of the system itself. Only recently has it been possible to build lightweight and power efficient laser heads thanks to the use of laser diodes instead of flash lamps as a primary light source. To be able to use laser ignition in a vehicle one must also ensure that the optics that guide the beam inside the combustion chamber is not affected by the heat and vibrations close to the engine.

Another issue is safety. Even scattered reflections of a powerful laser beam has enough energy to cause permanent damages to the eyes. A laser powerful enough to ignite fuel must be kept enclosed so that laser light can never escape the ignition system. This is especially important when dealing with infrared light since a leak may not be discovered before the damage is done.

Design

During the design phase of the project the main concern of the laser ignition sub-project was to find suitable equipment to be used in the construction of a laser ignition system that could be used on the engine. The desired specifications of this equipment was decided.



Optical plug consisting of lens holder (background) and window holder (foreground)

Almost all lasers used in laser ignition experiments have been Q-switched Nd:YAG lasers. They can be made compact and energy efficient enough to be realistically installed in a vehicle, while also fulfilling the requirements regarding pulse energy and repetition rate.

Important Considerations And Design Parameters

This section contains descriptions of some important properties of laser equipment as well as some recommended values for these properties. It can be seen as guidelines for the process of selecting suitable equipment for use in the engine.

Optics

Another challenge when designing a laser ignition system is to create the best possible path between the laser source and the combustion chamber of the engine. The most important function of the optics is to focus the beam so that the focal point of the beam (where ignition will happen) is optimally located inside the combustion chamber. Typically a lens made from borosilicate glass is mounted in close proximity to the chamber.

To protect the lens from damage and pollution caused by the combustion process a window is usually installed at the end of the optical pathway, in contact with the inner wall of the combustion chamber. This window is typically made from sapphire or silica, and needs to be thick enough to withstand the pressure inside the combustion chamber.

There are different ways to mount the optics on the engine. One way is to install the glass window permanently in the cylinder head. This allows for more freedom in the choice of window dimensions since the cylinder head can be manufactured or modified to accommodate the window. The lens can then be mounted above the window. This setup also allows the user to move the point of ignition inside the combustion chamber in all three dimensions provided that the window has been made sufficiently large. This can be useful when trying to find the optimal point of ignition. One drawback of this setup is that the cylinder head has to be modified to accommodate the window. It is also harder to replace the window in case of failure.

Another solution to this problem is to mount the window and lens inside a container resembling a spark plug. This “optical spark plug” can then be installed in place of the conventional spark plug, without modifying the rest of the engine. One major benefit of this concept is that it allows for an easy comparison between spark and laser ignition without modifying the engine between tests. An optical spark plug can be designed so that the lens can be moved relative to the

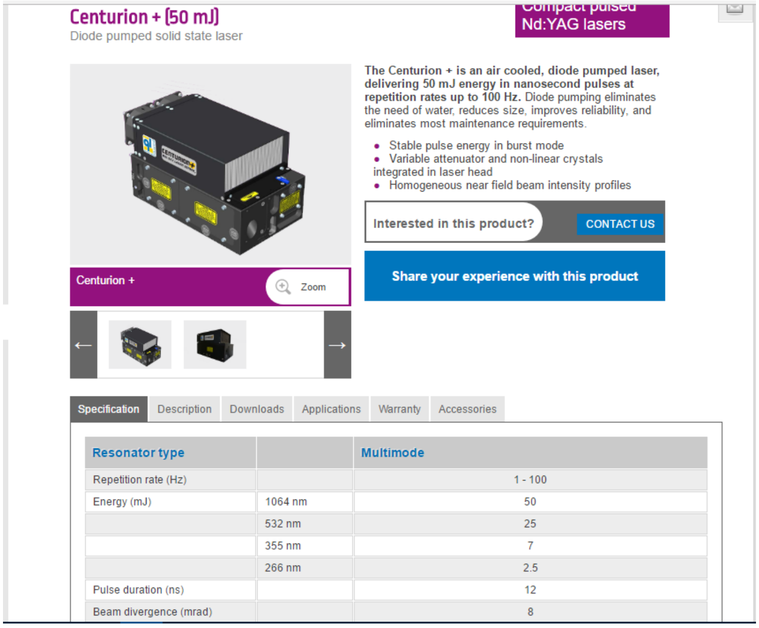
window, so that the point of ignition can be moved in one dimension. A simple design for an optical plug, was developed during the design phase.
If space is limited on the cylinder head the lens and window may have to be made small, with diameters of only a couple millimeters. In that case it is also important to consider the width of the laser beam. In some cases it might be necessary to narrow the beam using additional optics before it enters the optical path mounted on the engine.

Optics Pollution And Ablation

All internal combustion engines produce some amount of combustion by products. When running an engine fitted with an optical window such as is necessary for laser ignition, this window will eventually be coated in soot and other pollutants. Fortunately, experiments show that the laser is able to clean the glass through a process known as thermal ablation.
This basically means that the heat from the laser beam vaporises the polluting particles on the window and the system becomes self-cleaning. Additional laser pulses such as the aforementioned "waste spark" can be used to enhance this feature.
For long-term use of laser ignition systems it is uncertain whether this process of ablation may cause significant damage to the glass itself, eventually resulting in failure of the protective window. Since LI is still an experimental technology there is limited data on the long term wear on the ignition system.

Laser Selection

For the main component, the laser, it was decided that the best choice for this application would be a diode-pumped, Q-switched Nd:YAG laser with a pulse energy of at least 50 mJ and a repetition rate of 100 Hz. Ideally it would also be small enough to be easily mounted alongside the engine for testing.



Centurion + (50 mJ)
Diode pumped solid state laser

The Centurion + is an air cooled, diode pumped laser, delivering 50 mJ energy in nanosecond pulses at repetition rates up to 100 Hz. Diode pumping eliminates the need of water, reduces size, improves reliability, and eliminates most maintenance requirements.

- Stable pulse energy in burst mode
- Variable attenuator and non-linear crystals integrated in laser head
- Homogeneous near field beam intensity profiles

Resonator type		Multimode
Repetition rate (Hz)		1 - 100
Energy (mJ)	1064 nm	50
	532 nm	25
	355 nm	7
	266 nm	2.5
Pulse duration (ns)		12
Beam divergence (mrad)		8

Based on these specifications several lasers from different manufacturers were selected as potential candidates, but very few of them fulfilled all requirements. The most common issue was that the repetition rate was too low to be able to perform any meaningful testing. Other lasers were simply too large and powerful for our application.
The best candidate turned out to be the Quantel Centurion+ from Quantel Laser. It is a diode-pumped, Q-switched Nd:YAG laser with a maximum pulse energy of 50 mJ and a repetition rate variable between 1-100 Hz. This laser also has a compact design, is entirely air cooled and has an integrated power supply. The total weight of the assembly is 6 kg.

Optics Selection

It was decided early in the design phase to construct the optical pathway in the form of an optical spark plug for installation in the existing cylinder head. A design suggestion is provided above. The primary reason for this was to enable side-by-side comparison between spark and laser ignition without dismantling the engine. Because of the small size of the original spark plug used in the engine and the limited space available on top of the cylinder head the size of the lens and protective window had to be restricted. The proposed design of the optical plug uses a window 5 mm in diameter and a lens 6 mm in diameter with a focal point located 21 mm from the lens. This assembly can be mounted on the existing cylinder head without modifications. The design allows for some adjustment of the point of ignition.

CHAPTER 6

Direct Injection and Water Injection

Direct Injection-Introduction

Direct injection is a method of fuel injection which in this section is evaluated with regards to overall engine performance. The theory behind direct injection is described and the design chosen for the implementation in the technical demonstrator is described and motivated. The results are then presented and analysed.

Theory

There are several different methods for getting fuel into an internal combustion engine, most based on pumping pressurized fuel through a small nozzle, thereby atomizing the fuel. When a carburetor is used, however, the fuel is transported with the air as the fuel-air mixture is sucked into the cylinder during the intake stroke. The suction occurs as the pressure in the cylinder is lower than the air pressure in the carburetor.

The method for injecting the fuel into the cylinder by is port injection where the fuel is injected in the intake duct and then flows into the combustion chamber with the air as the intake valve opens. Another method for injecting the fuel is to use direct injection, DI, which is when the fuel is injected directly into the combustion chamber during compression using higher pressure than the in-cylinder pressure. Figure illustrates how DI works and how it differs from a standard port injected engine. The main theory of direct injection is that the higher fuel pressure used creates smaller fuel droplets and a more atomised spray which can be evaporated faster. This is because smaller droplets have a greater combined surface area than bigger droplets, and therefore more contact with the surrounding air.

Relation Air And Fuel

The way that the air and fuel is mixed can be described in different ways. If the air and fuel are mixed so that precisely all the fuel and oxygen in the air are combusted with no excess air, the mixture is called a stoichiometric mixture. For pure octane, the stoichiometric mixture ratio is 14.7:1, that is 14.7 mass parts air and 1 mass part fuel. Another way to measure the ratio between air and fuel is to use lambda, λ, which describes the relation between the combusted air and fuel residuals in the exhaust fumes. For a stoichiometric mixture λ equals 1.0, rich fuel mixtures has a $\lambda < 1.0$ and lean fuel mixtures $\lambda > 1.0$. After combustion rich fuel mixtures still contains uncombusted fuel. This occurs when there is not enough oxygen molecules to combust all the fuel molecules. Lean mixtures has on the other hand more air than needed and this mixture results in uncombusted oxygen. The air-fuel mixture which is to be ignited is also called the charge.

Lean Mixture

An engine is usually dimensioned to provide enough power for its maximum load condition. However many engines mostly operates during much less load and the power required is therefore much lower. This means that the power needs to be cut at this operating point which is done in most engines by using a throttle that is kept partially open to reduce the air flow. The air then needs to be pumped through the throttle which causes losses in efficiency.

By employing a lower air-fuel ratio, AFR, i.e. a lean mixture, the throttle can be kept almost fully open and still achieve the required power, thereby reducing the throttle losses. This mixtures does however mean that the exhaust after treatment is more complicated and the lean mixture can therefore increase the amount of NO_x emissions.

Rich Mixture

By using a rich mixture, then it is possible to gain more torque from the engine. This is because in a rich mixture, the hydrocarbon in the fuel reacts with the oxygen, and as there is a deficit of oxygen, carbon monoxide is created. In a lean mixture, where there is more oxygen, carbon dioxide is created. When carbon monoxide is created more energy is released which heats the gases and more torque is achieved.

Advantages And Disadvantages

A main advantage using DI is that it offers the opportunity to achieve higher torque and power than port injection. One of the reasons for this is that the potential for charge cooling is increased. Charge cooling is when the charge, intake air, is cooled and hence the density is increased. This increases the volumetric efficiency as more air molecules can fit in the same space. In a DI engine where the system uses highly pressurized fuel there is a higher probability that the fuel is vaporized before hitting any chamber surfaces. This means that the energy used to evaporate the fuel is transferred from the intake air instead of the chamber surfaces, and charge cooling occurs. This increases the volumetric efficiency by 2-3 %. By decreasing the charge temperature, the probability of knock is decreased due to lower compression temperatures. When the fuel hits the chamber surfaces it is called walled wetting and it common in port injection. When the fuel hits the chamber surfaces, the energy needed to evaporate the fuel is transferred from the surface to the fuel, instead of from the surrounding gas. By transferring the energy from the surfaces it cools the surface and decreases the volumetric efficiency of the engine, as the potential for charge cooling is decreased.

Another advantage of DI is that the fuel does not displace the air, as port injection does, which means that the air trapped in the cylinder is increased, thereby increasing the volumetric efficiency.

A drawback with DI is that it requires that the fuel injector nozzle is mounted directly into the cylinder, the materials need to be more durable than when the injector is placed in the intake manifold. This means that the injector needs to be made of a material with a high quality which is expensive. The pressure with which the fuel is injected into the cylinder also requires costly high pressure fuel pumps.

Water Injection-Introduction

Water injection is relatively a very new technology in the automotive sector. The major drawback of using lean mixture with direct injection is that there will be high amount of NOx produced and the power and torque figures will be significantly lower, thus reducing the overall performance. Hence, water injection was introduced.

Though the name suggests “water injection”, it’s not exactly pure H2O that is supplied. It is actually a 50-50 mixture of methanol and water.

Theory

The theory behind water injection is that the intake air is extremely hot and even though intercoolers help a lot in bringing the temperatures down, there’s still a significant amount of heat present in the intake air. The intake air coming in to the cylinder is always desired to be

cooler, as cool air is much denser and hence more air can be accumulated and hence better combustion. Also, if the intake air is too hot the chance of predetonation also increases drastically.
So, to avoid all the above problems and at the same time improve the overall performance of an engine a new technology was devised.

The Mechanism

The performance achievable by a combustion engine is limited by various factors, including the process temperature in the combustion chamber. If this temperature is exceeded, the result is uncontrolled combustion (knocking) and thus a loss in performance and, in the worst case, expensive damage to the engine.

This is particularly important when the engine is charged, as the intake air is already heated intensely in the turbocharger's supercharger.

An intercooler does ensure that the temperature drops as necessary, but even that has ist physical limits. Depending on design and dimensions of the cooling system and the car's aerodynamics, the intake air reaches temperatures that are just below the maximum permitted temperatures.

Increasing the supercharging pressure would exceed the knocking limit and is therefore not a viable means for increasing performance. The solution is injecting a fine spray of water into the collector once more significantly reduces the temperature of the combustion air.

The cooler supercharged air reduces the engine's tendency to knock, making it possible to bring the point of ignition forward and thus closer to the optimum value. This makes the combustion process more effective, whilst at the same time reducing the combustion temperature. On the other hand, cool air has a higher density which increases the oxygen content in the combustion chamber. This results in a higher mean pressure during the combustion process and in turn optimises performance and torque. Finally, the effective internal cooling of the combustion chamber reduces the thermal strain on numerous performance-related components. This not only prevents damage to pistons, exhaust valves and catalytic converters, but also reduces the strain on the turbocharger, which is subjected to lower exhaust temperatures.
The lower process temperatures also reduce the formation of hazardous substances, in particular nitrogen oxide (NOX). Water injection consequently dramatically improves the effectiveness of the engine.
Using water injection to increase the knocking limit also helps to largely resolve a familiar conflict in objectives when designing powerful engines. Performance and consumption are not least determined by the compression ratio. A high compression ratio engine is highly efficient and boasts low consumption figures, especially in the partial load range. However, the maximum compression ratio is limited by the knocking tendency when fully loaded. Water injection is also hugely beneficial here, as it reduces the tendency for the engine to knock, whilst at the same time increasing the compression ratio.

When positioning the water injection, a layout with three injection valve in the plenum chamber, supplying the cylinder was decided. This solution ensures very equal distribution and also allows the system to be designed in a compact manner. This design can also be used in a multi-cylinder engine, without much modification.

Water tank needs to be placed somewhere which also houses the water pump, sensors and valves. The pump and complete system of sensors and actuating elements are controlled by the engine electronics. In practice, the pump has to feed the water to the injectors at a pressure of ten bar, whereby the appropriate volume is supplied depending on load, engine speed and temperature. This ensures that water consumption is kept to an absolute minimum. In rigorous action, it is always necessary to refill the water supply whenever refuelling is done.

Design

Water Injection System

The above diagram gives a brief of the design. The injector is placed very close to and just before the throttle body. The injector should be capable injecting at 10 bar pressure. An electronic pump is fitted to supply the water-methanol mixture to the injector. The tank to hold water is placed at the end of the line. The tank should be frost free, as is the normal fuel tank to avoid freezing in negative temperatures. The pump also keeps the line empty during non-working condition, and supplies the water back to the fuel tank.

The basic principle here is liquid supplied at high pressure and therefore changing the state of water from liquid to gas. In order to do this high energy is required and hence most of the heat is used up. This cools the intake air going in the combustion chamber. This effect can be related to sweating. Water is released in to the skin, the sweat starts evaporating and changes its state and it feels colder.

Why Water And Methanol?

Water is an incompressible liquid with its own uniqueness and vast availability. Water has the perfect temperatures of boiling and it also evaporates at a good rate. However, the main reason to select water is that it takes up a lot of energy to change its state. The cooling effect that water provides is also significantly higher.

Methanol on the other hand can also be added as an additive. Since this cannot be abundantly used and finding methanol at every fuel station is also not possible hence the system can work alone with just water only. However, adding methanol will significantly improve the octane number. This can help in advancing the combustion to its theoretical value and hence more efficient engine can be obtained. Methanol is also combustible unlike water and can also help in obtaining complete combustion.

CHAPTER 7

Results and Discussions

Coating

The ceramic cylinder liner was designed to withstand the compressive stresses of the preload between the cylinder head and the cylinder.

Cylinder liner made of ceramic

Cylinder Liner made of CI(usually)

An interesting test would be to compare an engine with parts made of ceramic material with a conventional engine at the same AFR and measure the cylinder pressure and the exhaust temperature. In this way it is possible to track the released energy of the fuel and to compare energy split between friction and heat losses, mechanical work and energy in the exhaust gases.

A comparison between solid ceramic parts and coated parts are suggested to be carried out, in terms of fuel efficiency, durability, wear, manufacturing simplicity and cost.

The impact on piston rings with a ceramic surface on the cylinder liner is also an important aspect. First, testing the possibility to combine a ceramic liner with low-friction PTFE piston rings could decrease the friction losses considerably if these piston rings can withstand the temperature and pressure with long enough life span. Wear and friction rates on conventional piston rings abuts the cylinder liner are also suggested in future work.

Otto To Atkinson

In this paper, the investigations of Atkinson cycle converted from conventional Otto cycle gasoline engine have been conducted through theoretical calculations. The main conclusions of this study can be summarised as follows. A MATLAB code has also been created to verify the same.

1. In order to achieve higher engine efficiency and better fuel economy, the CR was increased from 10.5to 13 by reducing the clearance volume by redesigning piston top configuration.
2. The intake and exhaust cam profile have been redesigned based on the original Otto cycle engine to meet the Atkinson cycle engine valve timing requirements by increasing main intake cam length angle, LIVC, and by reducing the valve overlap angle.
3. The BSFC of Atkinson cycle engine is much lower than that of original Otto cycle engine, especially at low medium speed. Moreover, the low fuel consumption and high thermal efficiency area of Atkinson cycle engine is much wider than that of original Otto cycle engine.

Laser Ignition

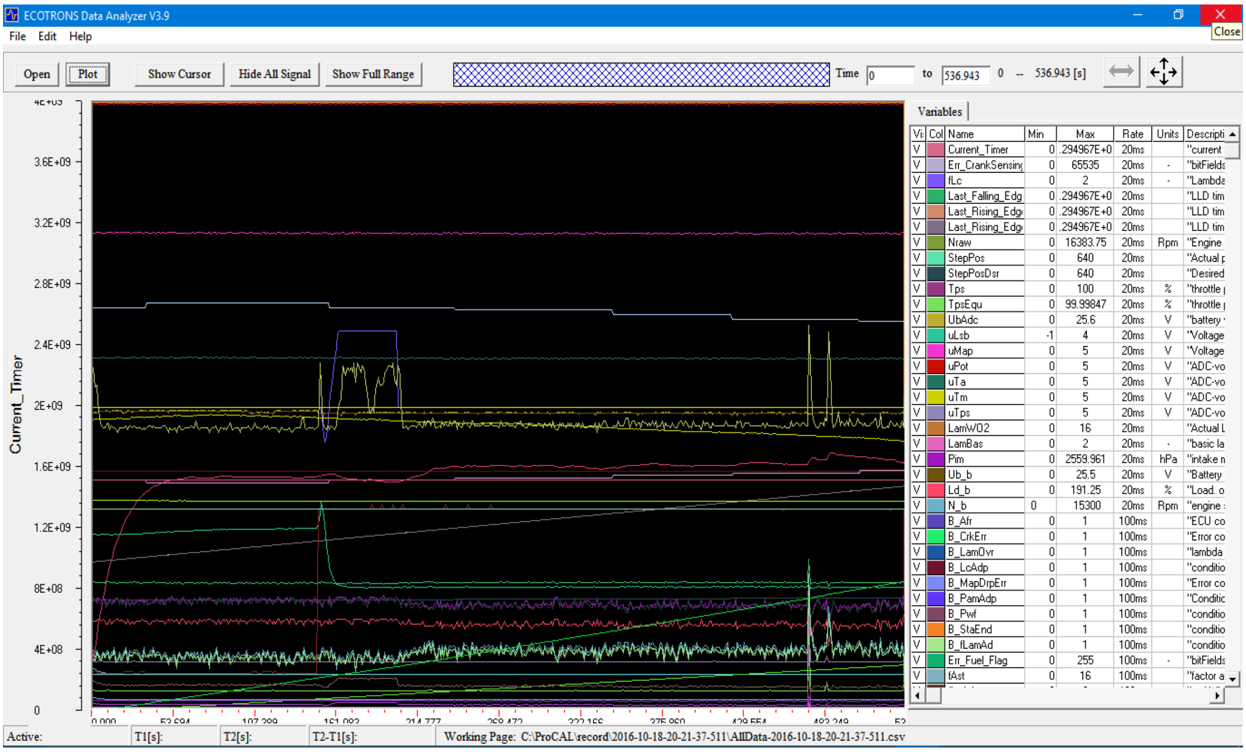
As stated in the introduction to this chapter, laser ignition remains a highly experimental technology. While it has been proven to have several significant advantages over regular spark ignition, there is still a lot of development to do before it can compete with conventional ignition systems in terms of cost. The yellow graph shows the difference between spark and laser ignition.

The values on the right also gives an evaluation. The comparison was made in the same cycle without stopping the observation. In the first cycle the spark plug spark intensity was given and in the second cycle laser intensity was given. The combustion values peaked whereas energy consumed and all other parameters remained constant.

Direct Injection and Water Injection

With all the advantages of direct injection and combining that with the water injection technology, significant leap forward in obtaining a more efficient engine can be obtained. At the same time reducing the emissions in running a lean mixture, thus improving on the fuel consumption when the particular mode is chosen.

At the same time, when racing during track purpose is required, the rich mixture can be opted for and the water injection rate will be increased, keeping the emissions level to the bare minimum and at the same time providing the required torque and power figures.



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V	⬛	StepPosDsr	0	640	20ms		"Desired
V	🟪	Tps	0	100	20ms	%	"throttle
V	🟩	TpsEqu	0	99.99847	20ms	%	"throttle
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