# *Hydrogen Enhanced Combustion*
# *History, applications and Hydrogen supply by plasma reforming*


***Georgios Pechlivanoglou***

*University of Oldenburg*

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***Abstract***

*Since the early years of internal combustion engine development, many researchers have been trying to optimize the combustion process in the engines' chambers. The utilization of hydrogen as a combustion enhancer have also been investigated during the years of the machine-dominated era, but the results were dubious. Therefore Hydrogen Enhanced Combustion (HEC) is not yet being commercially used. The aim of the following document is to present the milestones of the results on the HEC research, as well as the potential applications and the present state of the art on this field. Finally the possibility of on board hydrogen production with plasma reformer is also briefly presented and investigated.*

## Nomenclature

***TDC****: Top Dead Center. The highest position of a reciprocating internal combustion engine's piston.*

***BDC****: Bottom dead center. The highest position of a reciprocating internal combustion engine's piston.*

***HCCI****: Homogenous Charge Ignition Combustion*

***HEC****: Hydrogen Enhanced Combustion*

***Advance****: Ignition advance. The time gap (measured in crankshaft rotation angle) between the realization of the ignition arc and the TDC of the piston.*

***Retard****: Ignition retard. The time gap (measured in crankshaft rotation angle) between the realization of the TDC of the piston and the ignition arc.*

***CFD****: Computational fluid dynamics*

***EGR****: Engine gas recirculation*

***FSI****: Fuel stratified injection*

***Cylinder Fill Factor****: The factor that presents the percentage of the cylinder's volume which is actually filled with air (or air fuel mixture). For the normally aspirated engines the fill factor is between 0 and 1, while the supercharged engines have a fill factor higher than 1.*

***S.I****.: Spark Ignition (gasoline engines)*

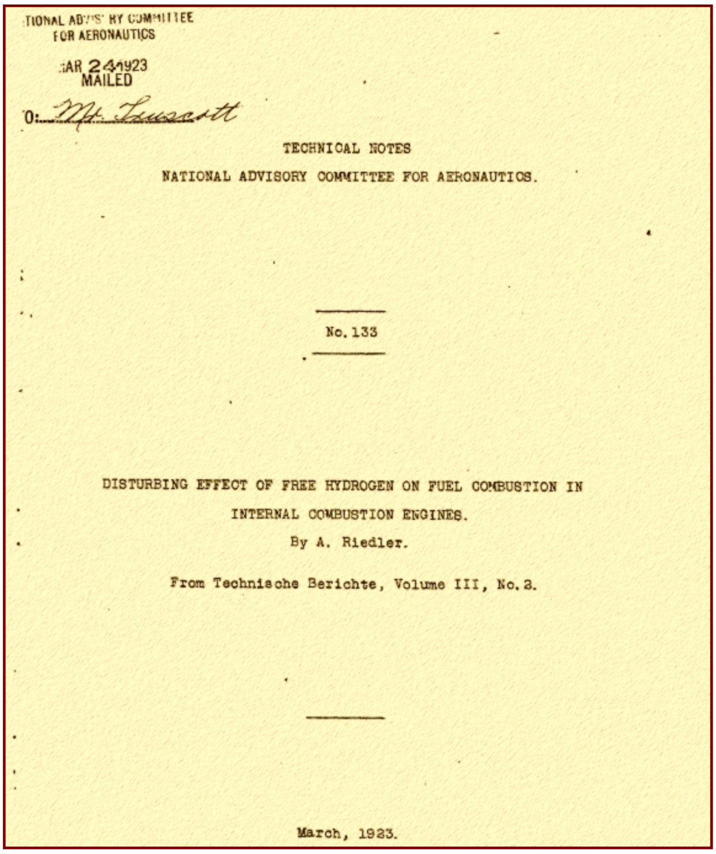
***C.I****.: Compression Ignition (diesel engines)*

***Inconel****: is a family of nickel-based superalloys. Inconel alloy 600 is 72% nickel, 16% chromium, and 8% iron. Other forms of inconel exist, each with slightly different additions. e.g. Inconel alloy 750 has a small percentage of titanium and aluminium added for hardenability. Inconel is highly oxidation and corrosion resistant, even at very high temperatures, and retains a high mechanical strength under these conditions as well*

***Historical Reference***

*Chemical Hydrogen Additives*

After the mobilization of the army in the 1st World War, the production of internal combustion engines rapidly increased. The engines became vital for many applications and the utilization of motorized vehicles became everyday reality. Therefore it was not a surprise that at the end of the first decade of 1900 a significant shortage in petroleum production was noted. Although many countries suffered from this shortage, the ones that had no oil reserves but highly developed industry came to a point where they could not meet the oil demands by any means. In Germany, a solution to the problem was the development of synthetic liquid fuels using the enormous amounts of coal available. The results of the German reports and the lessons learned from the experience of synthetic fuels were translated in English from the researchers of NACA (National Committee of Aviation) and presented in the form of NACA Report No.133 in 1923. The following paragraphs present and analyze the most important information of this report.



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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

No. 133

DISTURBING EFFECT OF FREE HYDROGEN ON FUEL COMBUSTION IN INTERNAL COMBUSTION ENGINES.

By A. Riedler.

From Technische Berichte, Volume III, No. 3.

March, 1923.

*NACA Report No.133*

The German synthetic fuel was a mix of benzol and alcohol in an 1:1 ratio and it was initially distributed at the military authorities. The term “fuel substitute” was replaced with the terms “improved” or “enhanced” fuel, for the purpose of better promotion of the fuel. This “enhanced” fuel was also accompanied with some “secret” fuel additives in the form of powder, which were supposed to enhance the engines performance. The addition of those substances was done just before engine start and it was taking place in the fuel tank of each vehicle. Those enhanced fuels were extensively used from military airplane pilots as well as racecar drivers during the late ‘10s and the results were surprisingly disappointing. Without exception, all the drivers or pilots were complaining about the performance of their engines when they used the “improved” fuels. In addition to the power deterioration, significant corrosion effects were noted at the moving parts of the engines that consumed “improved” fuels.

The obscure effect of the power deterioration and the complaints of the pilots and the drivers led to some more thorough investigation of the chemical structure of the enhancing substances and the results showed that the prevailing ingredient was potassium permanganate which was also combined with some other acidic substances of insignificant quantity. However, the existence of potassium permanganate in the fuel additives revealed the reason of the sever corrosion of the metal moving parts and this corrosive behavior of the “enriched fuel” was one of the reasons for its rejection from the German government.

However, the revelation of the corrosive effects of those fuel additives and the immediate rejection of those fuels “prevented” the investigation of the power deterioration of the engines and the correlation of this power loss with the chemical or thermodynamical behavior of the enhancing substances.

*Mechanical Hydrogenation*

Right after the failure of the chemical enhancement of synthetic fuel, researchers tried the solution of mechanical hydrogenation of the benzol-alcohol mixture in order to improve the combustion properties of the synthetic fuel. The level of sophistication in the enrichment of the liquid fuels with hydrogen was really impressive despite the lack of high-tech equipment. The final result was a homogenous liquid fuel, which contained significant quantities of hydrogen, having a chemical composition similar to gasoline coming from distilled oil. It is also important to note that this chemical bond of hydrogen gas and benzol-alcohol liquid fuel was so strong that in room temperature there was no sign of free hydrogen gas.

The thermodynamic tests, like the chemical ones, showed that the behavior of the hydrogenised benzol-alcohol fuel was close to the behavior of the normal fossil gasoline. The practical application of that fuel however revealed some other interesting results. The experiments, conducted at the Motor Vehicle Testing Lab of the Berlin Technical Highschool showed that the calorific value itself couldn’t fully describe the behavior of a fuel when this fuel is about to be burnt in a cylinder of an Internal Combustion Engine.

Actually, the results of the experiments showed that the engine output of an internal combustion engine decreases proportionally to the amount of hydrogen, which was introduced to the fuel at the enrichment procedure. In addition to the reduction of the engine’s output, there was also a notable increase at the fuel consumption of the engine and really obvious signs of combustion irregularities, which are realized as long and intensive flames at the exhaust system.

The abovementioned phenomenon seemed somehow impossible to explain, since the addition of a flammable gas in the fuel should lead to a better and faster combustion, which would therefore increase the power output and the efficiency of the engine. However the real trials showed exactly the opposite. The answer of this problem was a combination of chemical combustion reactions and internal combustion engine design properties. The analytical description of the causes of the disturbing phenomenon of hydrogen enrichment to combustion at the internal combustion engines can be seen below:

*Chemical Structure:* The benzol-alcohol mixture contains a portion of hydrogen, which is diluted at the whole volume of the liquid fuel. It is well known that hydrogen is the lightest element of the periodic table and possesses the highest calorific value. Those physical properties explain the high flammability of hydrogen as well as the low ignition temperature and fuel concentration that is needed in order to start and maintain hydrogen combustion. The mechanically hydrogen-enriched fuel used between 1915 and 1925 contained significant quantities of diluted hydrogen in its volume which was separated from the liquid fuel during the cylinder compression stroke and was rapidly ignited. The early ignition of the hydrogen caused a rapid increase of the cylinder's pressure due to the expansion of the hydrogen combustion exhaust gasses. This pressure increase was realized before TDC and caused an opposing force at the piston's motion, which was interpreted as reduced power output.

Additionally, as the hydrogen was combusting in a very short time with large amounts of oxygen (due to the increased amount of hydrogen in the fuel mixture), the combustion chamber was filled with water vapor and exhaust gasses (derived from the portion of fuel which was combusted). The superheated fuel vapor, which was not able to ignite due to the lack of oxygen, was escaping unburned at the exhaust and finally to the atmosphere. There, the mixture of the superheated vapor with the fresh air of the atmosphere caused the ignition and combustion of the unburned fuel in the form of spectacular exhaust flames.

*Engine Design*: The aforementioned situations were caused from the physical characteristics of the fuel mixture and especially of the hydrogen gas, which was used as combustion assisting agent. In addition to those factors, the poor engine design was adding to the general problematic behavior of the engines of that time.

The basic principles of the "ideal" combustion chamber design as they are formed nowadays (after decades of thorough research and experimentation) are:

- Hemispherical chamber with the spark plug in the middle of the chamber in order to create a uniform and evenly spread combustion.

- The highest possible compression ratio (depending on the fuel) in order to achieve high thermodynamic efficiencies.
- Small piston – cylinder gap and carefully calculated designed and manufactured sealing piston rings for minimized pressure losses.
- High velocity of the entering air-fuel mixture in order to achieve complete vaporization of the fuel and high swirl for homogenized fuel mixture (not valid for the Fuel Stratified Injection [FSI] technology.
- Carefully designed and manufactured metal parts (valves, spark plugs, cylinders, pistons) in order to avoid the "hot spots", which are responsible for the fuel pre-ignition and the reduction of the power output of the engines.

All those parameters and mostly the last one are responsible for the severe pre-ignition of those engines of the dawn of the 20$^{th}$ century and even more for the pre-ignition of the engines that consumed hydrogen enriched synthetic fuels. *(for further information about the engine design and combustion characteristics please refer to Appendix I)*

***The modern approach to HEC***

*Recent Development*

During the years of oil prosperity, almost nobody was interested in researching the HEC phenomena and to prove the initial experimental results, held by the Technical High-school of Berlin in the 1910s. However, after the oil-crisis of the 70s, some researchers decided to focus again on this forgotten issue and investigate it thoroughly. The paragraphs bellow, present a small synopsis of the key-points on the Hydrogen Enhanced Combustion investigation and experimentation, during the last 30 years.

- 1974. John Houseman and D.J/Cerini of the NASA Jet Propulsion Lab, produced a report for the Society of Automotive Engineers entitled "On-Board Hydrogen Generator for a Partial Hydrogen Injection Internal Combustion Engine".
- 1974. F.W. Hoehn and M.W. Dowy of the NASA Jet Propulsion Lab, prepared a report for the 9th Inter society Energy Conversion Engineering Conference, entitled "Feasibility Demonstration of a Road Vehicle Fueled with Hydrogen Enriched Gasoline."
- 1980. Prof. George Vosper (ex-professor of Dynamics and Canadian inventor), designed and patented a device to transform internal combustion engines to run on hydrogen.

- 1995. Wagner, Jamal and Wyszynski of Birmingham University, demonstrated the advantages of "Fractional addition of hydrogen to internal combustion engines by exhaust gas fuel reforming."
- 1995. HYPOTHESIS Conference, University of Cassino, Italy. A group of scientists from the University of Birmingham, UK, presented a study about hydrogen as a fraction of the fuel. In the abstract of that study it was stated: "Hydrogen, when used as a fractional additive at extreme lean engine operation, yields benefits in improved combustion stability and reduced nitrogen oxides and hydrocarbon emissions."
- 1997. At an international conference held by the University of Calgary, a team of scientists representing the Department of Energy Engineering of the Chinese University “Zhejiang”, presented a mathematical model for the process of formation and restraint of toxic emissions in hydrogen-gasoline mixture fueled engines.
- California Environmental Engineering (CEE) tested the HEC technology and found reduction on all exhaust emissions.
- The American Hydrogen Association Test Lab tested this technology and proved that: "Emissions test results indicate that a decrease of toxic emissions was realized."
- Northern Alberta Institute of Technology. Vehicle subjected to dynamometer loading in controlled conditions showed drastic reduction of emissions and improved horsepower.

These are just a few key-points in the recent Hydrogen Enhanced Combustion research and development history and they were presented in order to inform the reader about the major steps in the general field of HEC. However, the enormous size of the energy industry and the various designs of the Combustion Engines used today necessitate a more analytical description of the utilization of Hydrogen Enhanced Combustion, focused specially on each engine type. The following paragraphs present the results of the recent research on HEC at reciprocating Diesel and Otto engines, as well as in Brayton engines (gas turbines).

***HEC in Diesel & Otto Engines***

Reciprocating internal combustion engines were invented more than 100 years ago, but they are still dominating the market of small and medium output engines for all means of transportation and power generation. Almost all the engines around the world work according to the thermodynamic cycles of Otto and Diesel (Miller – Atkinson cycle reciprocating piston engines are scruple) and use many kinds of liquid and gas fossil fuels such as gasoline, diesel, bio-diesel, LPG and natural gas. The abovementioned thermodynamic cycles have many significant differences in the operation procedures but as the knowledge of the basic operation principles of those cycles is considered fundamental, the following text focuses only on the only points that that are relevant to the combustion phase of both Diesel and Otto cycle engines.

It is well known that the combustion process in gasoline and diesel engines is an intermittent process that occurs every four (4) piston strokes [see also Appendix I: The Otto cycle] . The duration of the combustion lasts just a few milliseconds and especially at the fast Otto engines, the available time for the completion of the fuel combustion if extremely small. Therefore engine designers and manufacturers are trying to improve both designs and manufacturing processes in order to produce engines capable of generating significant amounts of power with the minimum possible amount of fuel consumption. A key factor for the achievement of increased fuel efficiency is controlled, complete and rapid combustion of the fuel at the combustion chamber with the maximum possible amount of air.

The research over the past years has shown that the leaner a fuel-air mixture is the slowest the combustion becomes. This occurs mostly due to the fact that the fuel molecules are widely separated by air molecules and it becomes harder and harder to achieve a chain combustion reaction. In conventional gasoline or diesel engines, the flame propagates into the combustion chamber in the form of a flame front, which begins from the center of the chamber (where the sparkplug or the diesel injector is located) and moves towards the chamber walls, while ignites all the molecules of the unburned fuel. If we assume that a lean air-fuel mixture is about to be burned in a gasoline engine with 4° Advance, then the completion of the combustion would occur almost 170° later when the piston is almost reaching the BDC. This phenomenon leads to general efficiency and output degradation due to:

a) Maximum combustion pressure reduction due to the movement of the piston (increase in the combustion effective volume).
b) Reduction in the specific torque due to the reduction of chamber pressure (reduced piston force).
c) Increased heat losses due to the exposure of the cylinder walls to the hot combustion gasses.

d) Increased CO and unburned HC emissions due to the incomplete combustion of some isolated fuel molecules at the boundaries of the combustion chamber.

At this point it would be of use to repeat the previous example of the combustion in a gasoline engine, but now the fuel would be hydrogen-enriched gasoline. The enrichment of the gasoline is not realized via chemical or mechanical "doping" of the fuel, but with direct injection of hydrogen gas into the chamber or at the air intake in the vicinity of the inlet valve (different concepts being studied by the manufacturers). Back to the combustion example, where the sparkplug creates the ignition spark and the combustion begins 4° before TDC. The hydrogen enriched fuel has already entered the combustion chamber and the fuel-air ratio is very small (lean mixture) in order to achieve high efficiency.

Just 2msec later hydrogen starts to ignite and because of the fact that it is under high temperature and pressure it starts to separate into atomic (nascent) hydrogen. Nascent hydrogen is very active and produces a rapid chain reaction that spreads almost instantly to the whole combustion chamber volume. The almost simultaneous ignition of hydrogen initiates the simultaneous ignition of the main fuel, which is burned instantly without creating any flame front since the whole combustion chamber is being ignited at the same time. This combustion bares significant resemblance to the HCCI combustion which is created with physical means (rapid cylinder pressure increase), but the analysis of the combustion characteristics of the HCCI combustion is beyond the scope of this document.

The combustion process is now completed about 6-10msec later and after the piston has moved only 14-18° after TDC. This rapid combustion phenomenon results to:

a) Complete combustion of the whole chamber's volume without un-ignited areas.
b) Development of very high pressures at the combustion chamber due to the high temperatures and due to the fact that the combustion chamber volume is not significantly increased (the piston moves less than 20°). This leads to increased piston forces and increased engine torque (around 30% increase).
c) Ability to combust effectively extra-lean air-fuel mixture, which would not ignite under the conventional combustion engines. This leads to higher efficiency and increased fuel economy (around 25-30%).
d) Reduce (or even eliminated) CO and unburned HC emissions due to almost perfect combustion.
e) Reduction of NOx emissions, due to a complex mechanism of combustion mechanics, which was just recently understood and will be explained at the following paragraphs.

From the description above it becomes obvious to the reader that Hydrogen Enhanced Combustion poses significant advantages over the conventional combustion and it is considered to be one of the most promising techniques for the "clean" internal combustion engines of the near future. However some interesting issues about the operation of the HEC engines, which should be discussed in more detail are the reduction of Nitric Oxide emissions (NOx) and the method of hydrogen injection in the combustion chamber. [3]

***Emission reduction***

Between the engine manufacturers was generally approved that the increased combustion temperatures and the minimal duration of the combustion process were causing the formation and emission of Nitric Oxide pollutants. This was especially evident at the Diesel cycle engines where the compression and supercharging pressure increase was followed by a proportional increase of the NOx emissions. As a result of the above, the engine manufacturers have to compromise between performance and emissions, so they produce engines that cannot operate at the maximum temperature – pressure conditions while in the same time they have to utilize exhaust catalytic oxidation devices in order to achieve fully oxidized emissions. However both researchers and manufactures consider the present status as the threshold of the present engine design and they try to introduce less conventional methods in the design and manufacturing process in order to by-pass the emissions' barrier. This is the first step for this new era of engine design in the Hydrogen Enhanced Combustion, which promises multiple improvements in power production, efficiency and emissions.

As discussed above, the hydrogen is sprayed directly in the cylinder or at the inlet manifold very close to the inlet valve. The combustion is rapid and the combustion temperature very high, however the NOx formation is avoided due to the inherent characteristics of this kind of combustion. The NOx reduction at first seems impossible, since the high temperatures and the short duration of the combustion assist the NOx formation, but during the Hydrogen Enhanced Combustion the NOx-formatting chemical mechanism is "bypassed". The combustion is so rapid that the high temperatures exist only for approx. 2msec and almost the whole expansion stroke is not involving any combustion processes. This means that during expansion, the temperature inside the cylinder is lower than in the conventional engines, therefore the only time for the NOx to be formed is during the minimal period of the combustion. The result of this interesting phenomenon is the impressive reduction of NOx emissions in the engines that operate with HEC.

The abovementioned result is not achieved only in the highly controllable environment of the labs, but during the normal operation of the engine as well. Recently some experiments were conducted by Bowden Alberta Institution (Canada) in order to examine the real behavior of a vehicle equipped with a HEC Engine in the normal driving conditions. The results confirmed the devious experimental results since the CO, HC and NOx emissions were dramatically reduced and at some "driving profiles" CO and NOx emissions were eliminated (undetectable).

***The significant role of Hydrogen Injection Pattern***

Until now the fundamental issues around Hydrogen Enhanced Combustion were discussed in extent and it is obvious that HEC possesses many advantages regarding the engine emissions' levels and power output. However, when it comes to the realization of HEC at the massively produced internal combustion engines, the designers face some other problems concerning some really important details. One of those "minor" issues that play an important role at the operation of the HEC engine is the hydrogen injection.

*Indirect injection for S.I Engines:* In order to achieve HEC at an Internal Combustion Engine, Hydrogen (or gas mixture rich in hydrogen) must be mixed with the regular fuel. This can be done either directly in the combustion chamber or just before the combustion chamber at the air inlet plenum. Both alternatives have been (and still are) thoroughly examined by the researchers at the University or Industrial Labs that study HEC. When the hydrogen is injected at the air-intake, the structure of the whole system is simple, the modifications of the original engine are minor and the cost of those modifications is low. However, Hydrogen is difficult to handle since it is very light, very diffusive and is characterized by a very low ignition energy value (and temperature). This means that when the fresh air-fuel-hydrogen mixture moves inside the combustion chamber it can be easily ignited from the various hot spots inside the cylinder, such as the exhaust valves, the sparkplug, the carbon remains which are adhessed at the combustion chamber walls e.t.c. This pre-ignition of the hydrogen causes many problems, the most serious of which is the "back fire". This is a dangerous situation where the first portion of the ignited hydrogen ignites the hydrogen that follows and the combustion rapidly moves out of the chamber towards the air intake. Some engine manufacturers have studied the "back fire" phenomenon thoroughly and state that they have developed effective solutions for this problem, however most of the manufacturers who enter the HEC field, prefer to "play it safe" and go for the Direct Injection method.

*Direct injection for S.I Engines:* Direct Hydrogen Injection is much more expensive than indirect injection and requires major modifications at the existing engines in order to be retrofitted, but on the other hand it offers many advantages. Usually the injector is placed at the center of the combustion chamber (at the "traditional" position of the sparkplug) in such a way that the displaced and usually inclined spark plug is positioned close to the injection point. This placement of the spark plug and the injector assures a fast ignition of the fuel no matter how lean the mixture may be. In addition to that the "back fire" phenomenon is totally eliminated and the combustion can be more precisely controlled.

One of the most crucial variables of the Direct Injection Engine operations is the fuel injection timing. When the engine uses conventional fuel (e.g. gasoline) the injection starts many degrees of crankshaft angle before the TDC in order to provide sufficient time to the injected fuel to mix with the air in the combustion chamber. However when the engine uses hydrogen or pilot hydrogen (as a combustion stimulant) this delay is not necessary anymore. The combustion of hydrogen is more than 10 times faster than before and the combustion of the whole chamber volume can be realized in just a few milliseconds [3]. The following photos and diagram describe the Hydrogen Enhanced Combustion of a S.I. Engine in more detail.

S.I. Engine – Hydrogen jet combustion

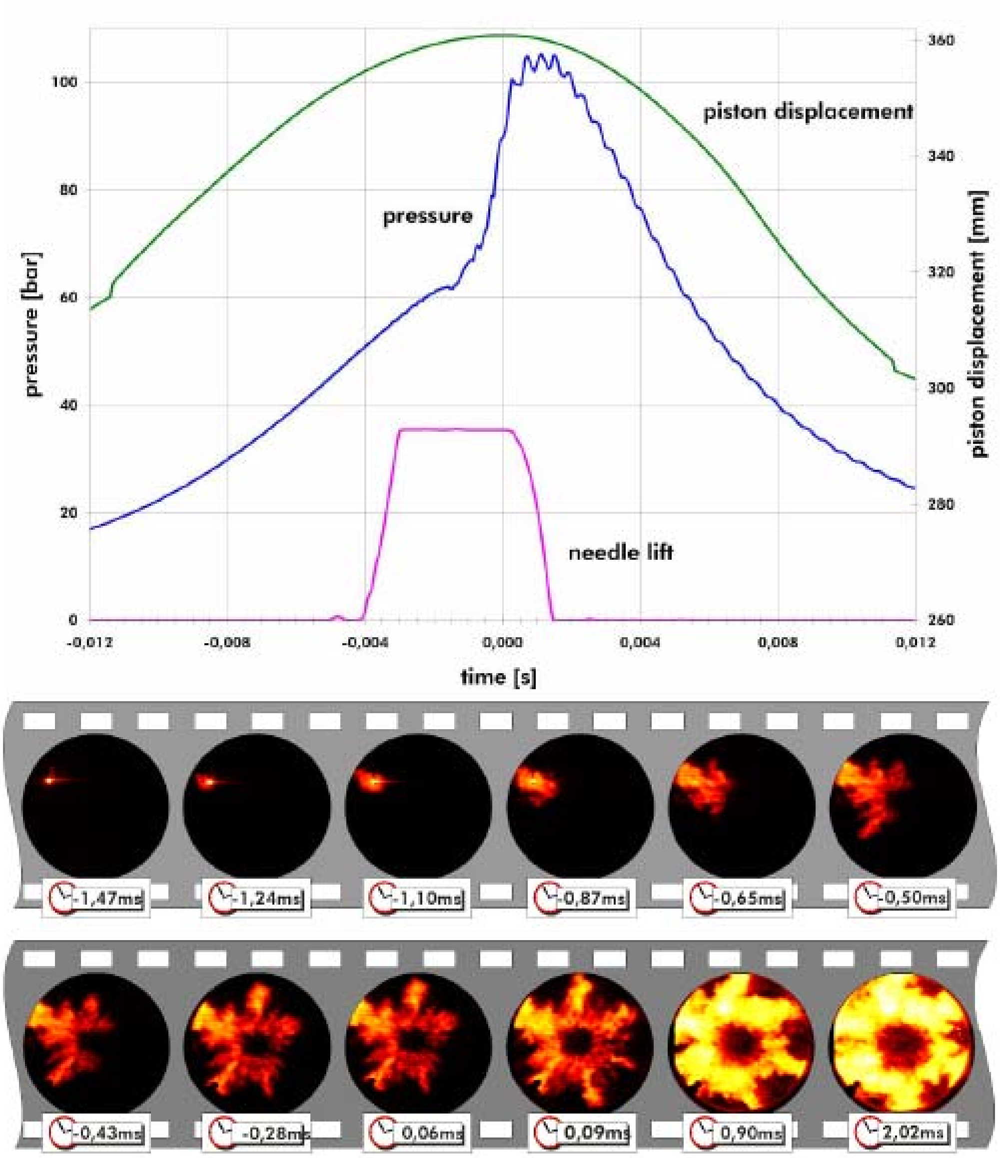



**Figure 1. Diagram of pressure and piston displacement during the combustion in a S.I. engine. The snapshots present the combustion process in steps of a few milliseconds** [3]

The image above describes the combustion process of a hydrogen jet inside a S.I engine. Looking at the sequence of images inside the combustion chamber, we can observe that the duration of the whole combustion process is only 3.5msec, which represents a few degrees of the crankshaft angle. The spark advance is just 1.47msec before the TDC and as it was described above, the sparkplug is positioned near the perimeter of the chamber since the injector is centrally mounted. At the initial state of the combustion (until 1.56msec after ignition) the flame pattern is not so symmetric since the area around the sparkplug achieves a faster combustion than the opposite side. However, and due to the very high speed of combustion of hydrogen, after 1 msec the combustion is almost symmetric and the whole quantity of hydrogen is ignited without any major un-ignited areas.

Looking now at the pressure – displacement (blue line) diagram we can observe that around the TDC there is the maximum pressure of around 105 bar. It is also clear that this extremely high pressure is achieved for a very short time providing a very effective combustion without allowing the formation of NOx.

*Direct injection for C.I Engines:* In Compression Ignition engines the fuel (diesel) is self-ignited due the high pressure-temperature conditions in the combustion chamber. The compression ratio of those engines is very high (more than 22:1) and the combustion control is achieved mostly with the fuel injection system since there is no electric ignition system. In conventional diesel engines the fuel is injected from high-pressure needle injectors, which spray the fuel a few degrees of crankshaft rotation angle before the TDC. At the modern high output diesel engines there are significant improvements at the fuel injection system in order to increase efficiency and power output while reducing the emissions in the same time. The modern diesel engines use very high-pressure fuel pumps with interconnected fuel injectors in a *common rail*. The increased injection pressure increases the atomization of the fuel, therefore the fuel droplets are extremely small and the total free surface of the fuel is very large. Now the combustion is more efficient and the soot production is significantly reduced.

In addition to that, the injection pattern is modified and now there is a *pilot injection* many degrees before TDC, which reduces the engine noise and cools down the compressed air in order to avoid pre-ignition. Then, just before TDC the major fuel injection occurs and causes the total ignition of the fuel and the actual power production.

Controlling the self-ignition of diesel is a hard task, even though diesel is a stable and thoroughly studied fuel, therefore one can imagine that controlled self ignition of hydrogen is a very complicated procedure mostly because of the fact that hydrogen tends to ignite very easy by the engine’s hot spots. Recent experimental studies showed that when the engines are extensively simulated with CFD models, controlled hydrogen combustion is possible, both as a stimulating combustion for diesel engines or as main combustion for Hydrogen C.I. engines. However there are some factors that can play a very significant role at the combustion procedure, which have to be extensively studied. One of those factors is the pattern of the injected hydrogen, which depends on the shape, the area and the number of the injector nozzle holes. The following paragraphs describe the effects of the injector nozzle holes at the hydrogen combustion.

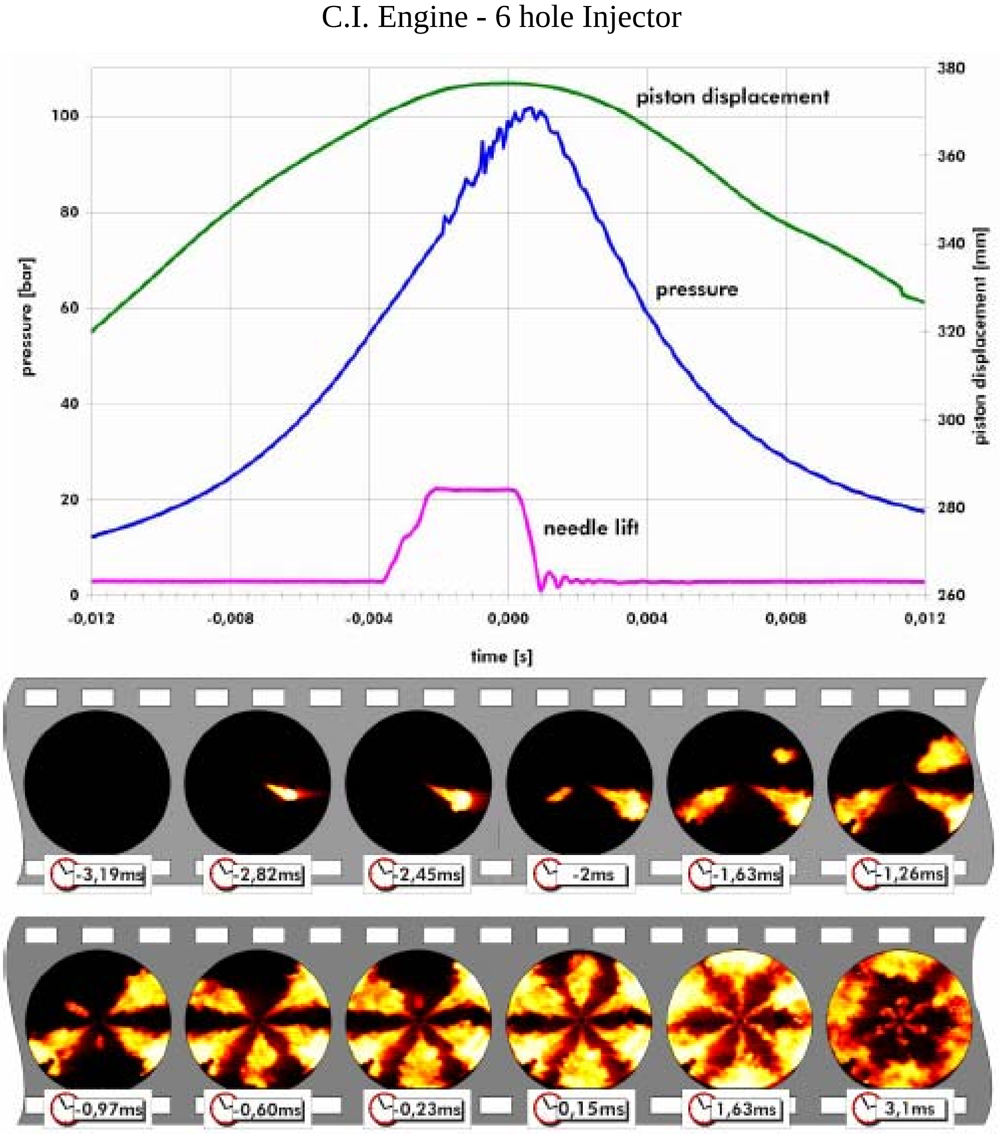



**Figure 2. Diagram of pressure and piston displacement during the combustion in a C.I. engine. The snapshots present the combustion process in steps of a few milliseconds** [3]

The injection starts 2.82msec before TDC and the ignition of the fuel is not symmetric at all. The first hydrogen jet is instantly ignited and within 0.8msec it has already reached the combustion chamber wall, while the second jet is just being ignited. This asymmetric combustion remains until the piston reaches the TDC when the whole chamber is under total combustion. The final molecules of fuel are burned 3.1msec after TDC and the combustion process is almost over.

Watching the pressure diagram (Fig.2) we can see the steep rise (up to 100bar) and fall of the pressure in the combustion chamber and also the smoother pressure curve during the symmetric combustion period (after the TDC). Looking at the combustion images we can clearly see the initial asymmetric behavior of the combustion, which is transformed to symmetric shortly after TDC. However is also interesting to note that there are some “black” areas at the images, which represent uncombusted regions or poorly-combusted regions. Those regions are mostly responsible for the emission of unburned HC and CO (if the engine is using the hydrogen combustion as a combustion stimulant).

C.I. Engine – Slotted Injector

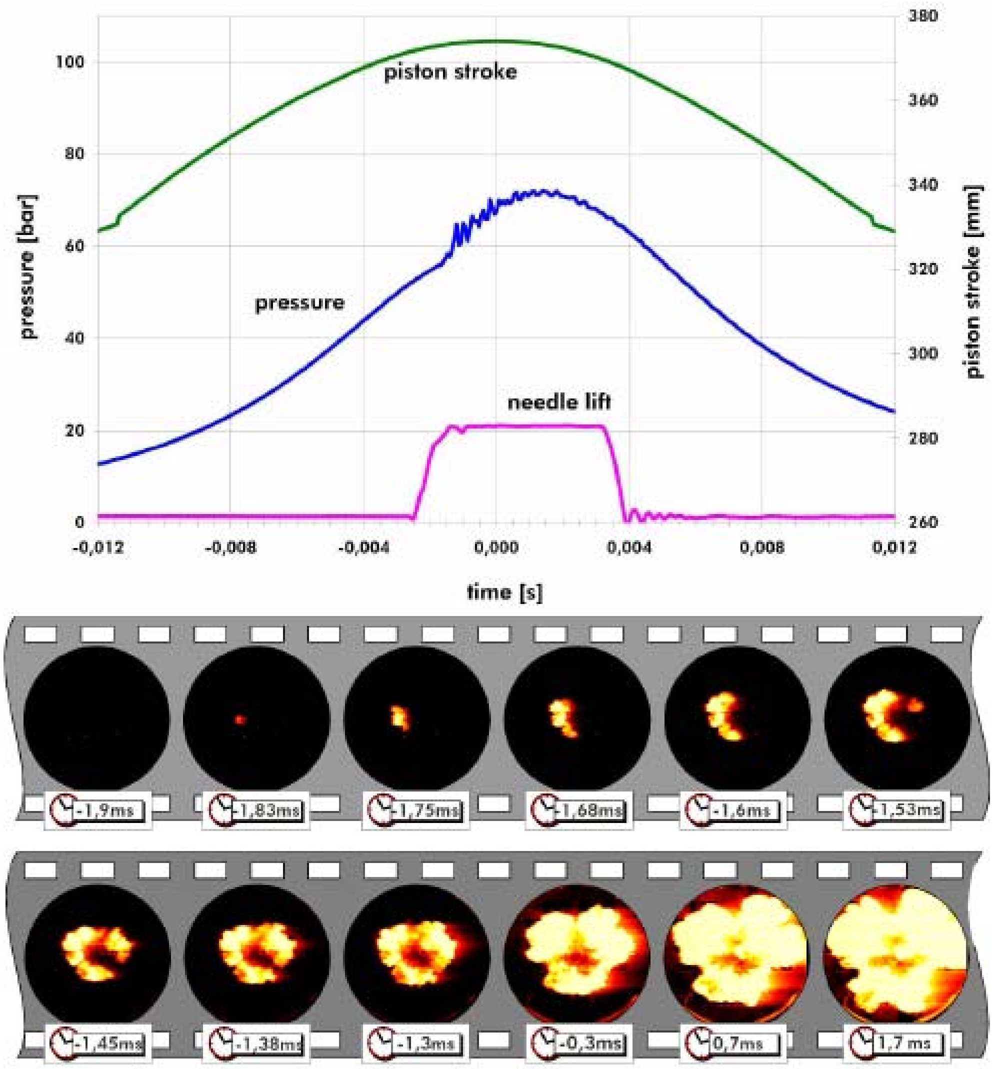



**Figure 3. Diagram of pressure and piston displacement during the combustion in a C.I. engine with slotted injector. The snapshots present the combustion process in steps of a few milliseconds** [3]

In the case of slotted injector nozzle (Fig. 3), the combustion develops in a totally different way. The injection and ignition of the fuel is much more symmetric, thus the combustion is more homogeneous. Approximately 1.83msec before TDC the combustion begins and 1.7msec after TDC the combustion process is spread at the whole chamber volume. The combustion pattern is much better than the previous experiment (6 hole injector) and also there are no “black” areas within the combustion volume. However it is obvious that there are some “black” areas of uncombusted fuel near the combustion chamber wall. Those are caused from the low velocity of the jet, which does not force the flame front near to the chamber wall and of course this effect will cause the emission of some CO and unburned HC.

Looking at the pressure diagram we can see that the pressure increase is smoother and less rapid than the previous examples, which means that the combustion process is more homogenous. On the other hand, the maximum pressure is significantly lower (approx. 70bar) than before, therefore the generated torque at the engine will be up to 30% lower!!

C.I. Engine – Hybrid Injector with holes and slots

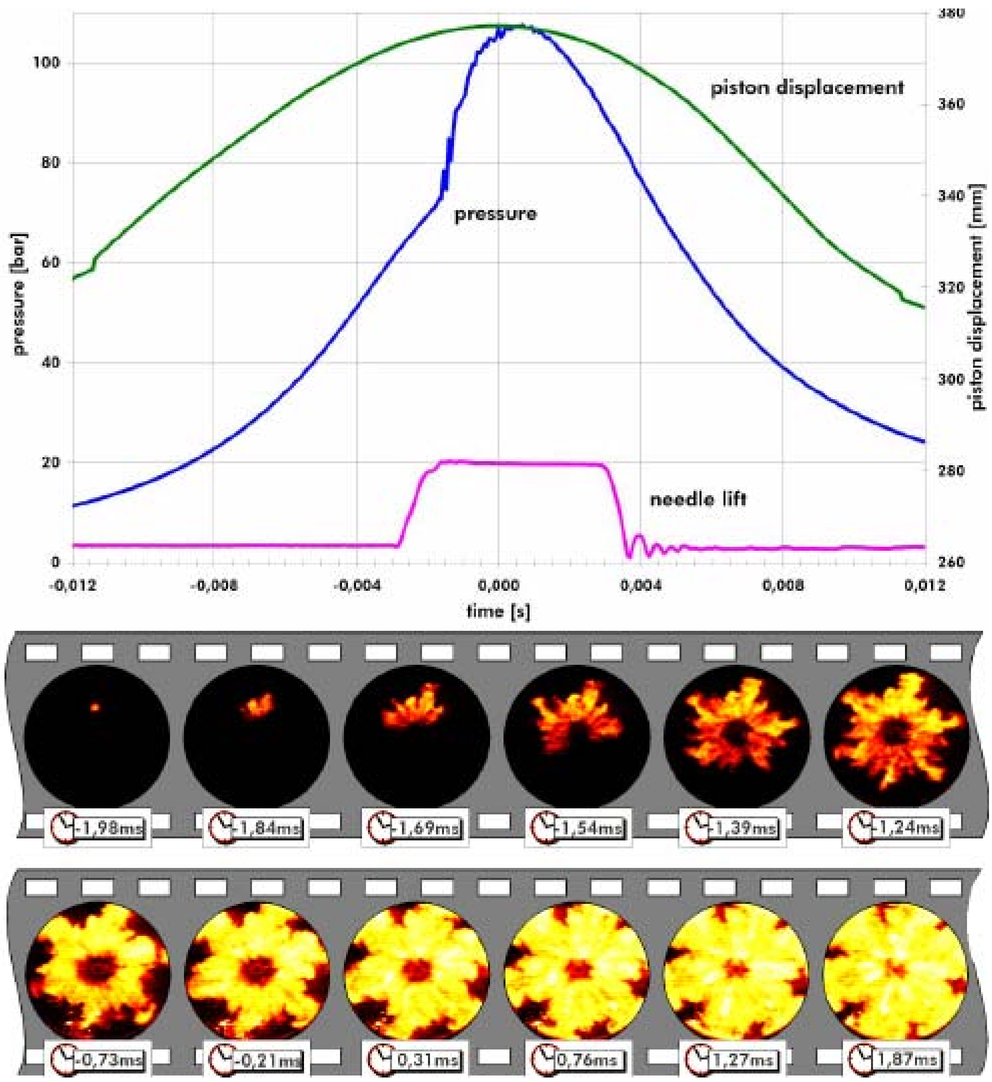



**Figure 4. Diagram of pressure and piston displacement during the combustion in a C.I. engine with a hybrid injector. The snapshots present the combustion process in steps of a few milliseconds** [3]

The last experimental setup examines the behavior of a hybrid injection nozzle (Fig. 4) that is equipped with holes and slots but with the same total area of injection. Now the ignition starts instantly, right after the injection of the fuel and spreads up rapidly and uniformly. The flame propagates rapidly in the combustion chamber and 0.73msec before TDC almost the whole combustion chamber is ignited. The combustion reaches its maximum volume around 1.87msec after TDC and the volumetric combustion coverage is the highest of all the experimental setups since there is almost no “blacks” area at the chamber.

The pressure diagram shows a very smooth but rapid pressure increase, which peaks at the value of almost 110bar!! In addition to that extremely high-pressure value, the duration of the combustion is very short and the pressure decreases very smoothly. This means that there is almost no emission of NOx and also the combustion is almost perfect without CO and HC emissions. The advantage of this setup is obvious as it offers beneficial results at both the efficiency and emission areas.

### *Gas Turbines and Hydrogen Enriched Fuels*

The reciprocating internal combustion engines are not the only engines that can be benefited from Hydrogen Enhanced Combustion, gas turbines can also improve their efficiency and reduce their emissions using hydrogen enriched fuels [7]. Recent experiments at NASA Glenn research center and SANDIA labs showed that the combustion of hydrogen enhanced methane in gas turbines can be stable and controllable even if the air-fuel ratio is very low. In addition to that, significant combustibility and flame stability is observed for various other fuels such as propane, butane, natural gas and even bio-gas.

The results of all the experimental procedures were in accordance with the theoretical predictions and it was noted that the addition of hydrogen to the injected fuel was beneficial both in the combustion speed, the lean mixture combustion and the emission reduction (or even NOx emission elimination in some cases). Regarding the speed of combustion it was found that the addition of very small quantities (less than 5% in weight) of hydrogen gas in the regular fuel increases the combustibility of the fuel up to 100%. This means that the combustion is much more rapid and efficient, leading to lower fuel consumption and higher overall engine efficiency [7].

Another advantage of the hydrogen enhanced combustion regarding the fuel efficiency is related to the ability of the engines to run with very lean fuel/air mixtures. The conventional gas turbines cannot operate with very lean mixtures since the widely scattered fuel molecules are not able to initiate and maintain a chain reaction which leads to a constant combustion. However the hydrogen enhanced combustion enables the gas to ignite and combust much more efficiently even if the fuel molecules are widely scattered within the combustion chamber of the turbine [8].

In general the implementation of hydrogen enhanced combustion at the gas turbines is considered to be relatively easy and trouble-free since the combustion is continuous and the fuel – air flow is more or less constant. In addition to that, the increasingly strict emission regulations will force the manufacturers to reject the current emission reduction method of water injection, which is just a compromise between the NOx and CO emissions reduction and integrate hydrogen enhancing devices at their turbines.

***On-board hydrogen generation***

As described in the previous sections of this document, the enhancement of the regular engine fuels with small portions of hydrogen leads to an amazing improvement of the engine efficiency and engine output, reduces the fuel consumption and almost eliminates the CO and NOx emissions. Therefore the implementation of this technology should be certainly considered as the innovation of the near future in the engine technologies. However, hydrogen's low energy density posses a serious problem when hydrogen has to be stored and carried in vehicles. Actually this is maybe the biggest problem that the "hydrogen economy" is currently facing and the main cause of the forecasted commercial failure of the hydrogen cars. Despite the recent development of new promising hydrogen storage technologies [5] and the fact that hydrogen enhanced combustion requires a very small amount of hydrogen in the range of 5% of the fuel weight, the storage issue is still a significant drawback. The most promising technology in order to overcome this problem is the *Plasmatron* [11] technology which was developed from MIT and Arvin Meritor. The following paragraphs describe the principle and major applications of this promising technology.

*Plasmatron (Plasma Reforming):* Plasmatron fuel reforming technology is being developed at MIT in collaboration with Arvin Meritor (vehicle-parts manufacturer) as a device which will allow practical on-board production of hydrogen enriched gas from a variety of fuels. This device is based on the use of low current, low power volumetric discharge in very high fuel/air mixtures. The process is slightly exothermic but the total system advantages overwhelm the disadvantage of lost heat [11].

Initially the plasma reformer device was developed in order to produce hydrogen, which would be burned in the NOx trap of the modern diesel engines. This hydrogen combustion would regenerate the NOx trap and maintain its good condition. However it was soon discovered that this innovation was much more valuable as a combustion enhancer than as a NOx trap regenerator, therefore the research and development focused on this new application.

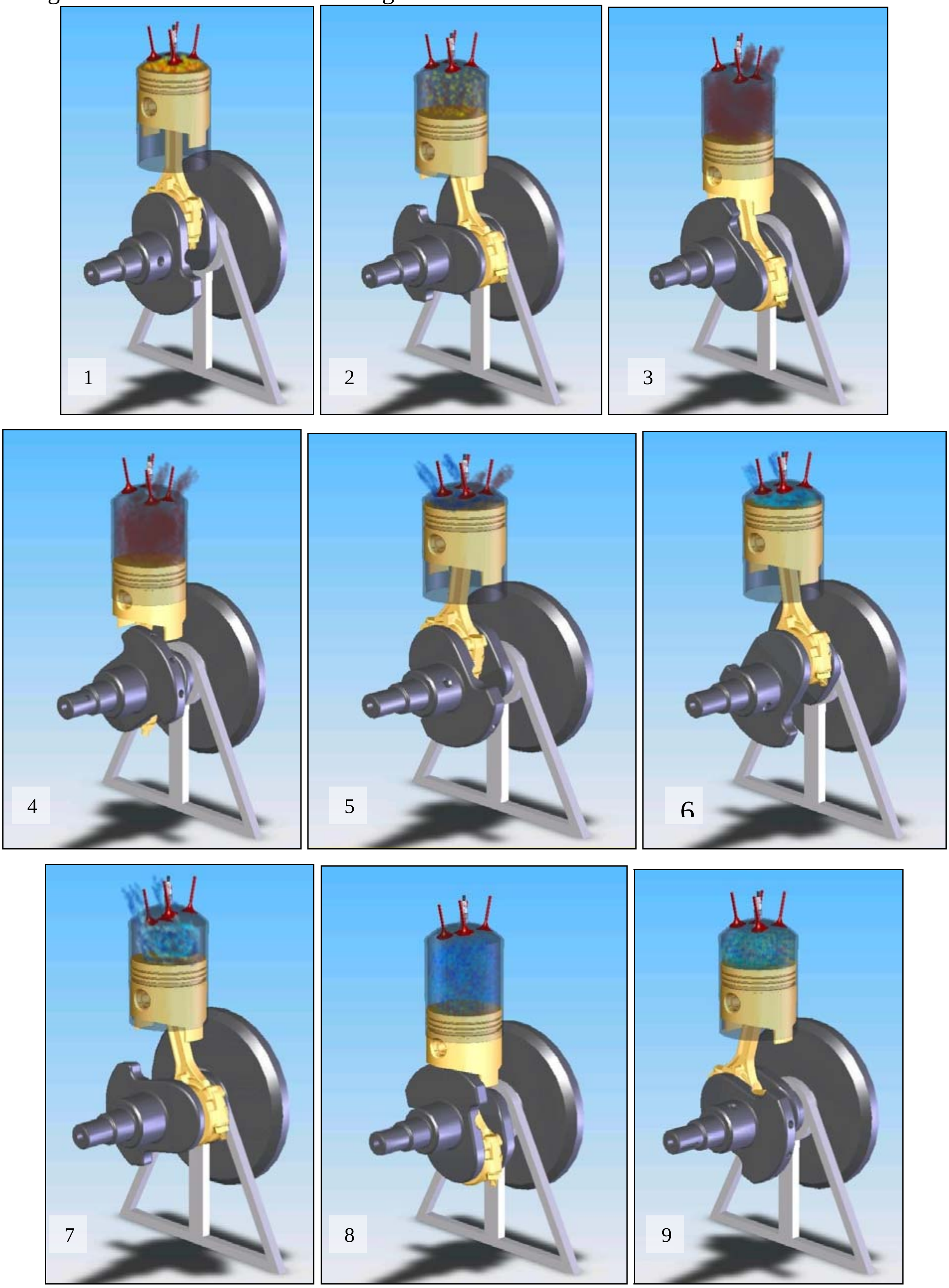
*Plasma reformer operation*: The plasma reformer consists of a plasma generator and a plasma reactor connected in series in a unified device. Rich fuel/air stream passes through the reformer where it is metered and the CPU determines the ideal degree of reforming. In the mean time high voltage (with high frequency) is applied to the air stream, forming plasma which is maintained while the air/fuel mixture passes through the reformer. The contact of the rich fuel/air mixture with the plasma initiates rapid partial oxidation chemical reactions which transform a small portion of the incoming fuel/air mixture. When the reformed gas exits the plasma reformer contains approximately 21% hydrogen, 22% CO, 5-6% small hydrocarbons, $CO_2$, water vapor and small quantities of Nitrogen.

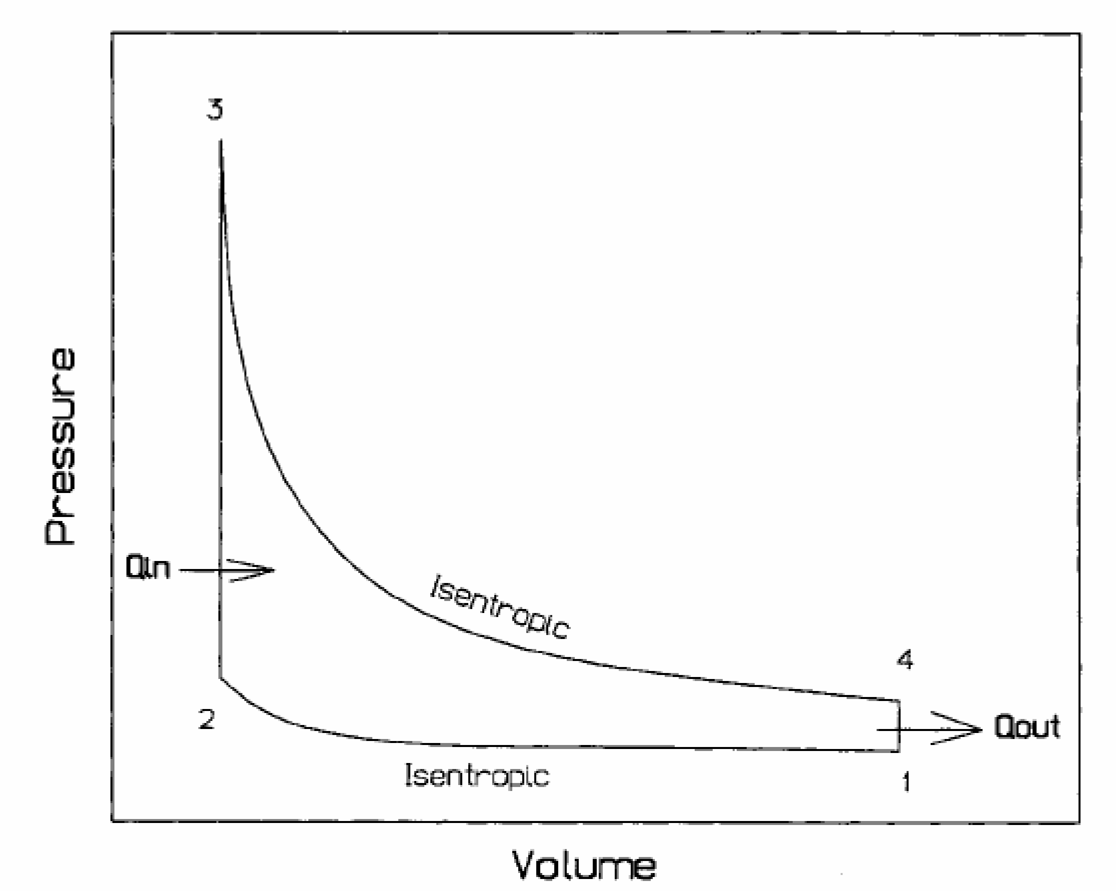
*Plasma reformer characteristics*: To generate the plasma, the plasma generator is equipped with a special power supply that transforms the battery power to high voltage, high frequency source. The early prototypes of plasma reformers were consuming almost 500W during their operation, but after intensive research and development at the labs of MIT, the latest versions of the plasma reformer consume just 75W of electrical power. It should also be noted that although all the commercially used reformers use catalysts in order to perform the partial oxidation of the fuel/air mixture, the plasma reformer does not use any catalysts. This lowers significantly the cost of the device, while it also increases its durability and reliability.

*Plasma reformer applications*: Due to the high reforming efficiency of the plasma reformer its applications are not limited to the diesel engines but can also be implemented to the gasoline engines, the gas turbines and even the normal burners. In addition to that, the reformer is able to operate with various fuels both liquid and gaseous such as Diesel, Gasoline, Kerosene, Propane, Butane, Natural Gas and even Bio-Fuels (corn oil, canola and soybean oil or bioethanol) [13]. Regarding the bio-fuel combustion, the utilization of the plasma reformer is considered to be extremely useful since it assists significantly the combustibility of those fuels that sometimes cannot achieve a satisfactory high efficient operation.

## Appendix I: "The Otto Cycle"

Spark Ignition – Internal Combustion Engine






*The Pressure – Volume diagram of the Otto cycle* [6]

**Snapshot 1**: Ignition – Combustion

- The spark is created at the spark plug and the air-fuel mixture around the spark plug is instantly ignited. The flame front propagates almost spherically (due to the geometric characteristics of the combustion chamber and the central placement of the spark plug) and the rest of the air-fuel mixture is ignited and combusted.
- The combustion velocity is increasing according to the 3rd power of the initial velocity (at least in theory) due to the spherical propagation. In reality the combustion velocity reaches a maximum value and then decreases due to the rarity of uncombusted air-fuel molecules. This deterioration of the combustion speed causes incomplete combustion at some places of the chamber, thus the engine emits some CO and some unburned HC.
- The air-fuel mixture is ignited and combusted. In theory this thermodynamic procedure is isochoric (volume = constant) while in reality the piston is moving rapidly towards the BDC during the combustion phase.
- The situation becomes worst due to the initial disadvantage of the crankshaft, which forces the piston to move faster around the TDC but slower around the BDC (a solution for this

problem is proposed by Honda Motor Co. in the form of reversed pistons with pooling rods instead of the conventional push rods).

- Another inherent problem of this configuration is the inefficient lever position of the system piston-rod-crankshaft. Therefore the maximum combustion pressure cannot produce maximum torque since it is occurring at the worst leverage point of the crankshaft, the TDC. The ideal combustion timing from a kinematics point of view would be 90$^o$ after TDC.
- The active area for the heat transfer during the combustion is minimum (only the ceiling of the combustion chamber and the piston crown). Therefore from a heat transfer and thermodynamic point of view the full combustion process should take place at this time/volume in order to minimize heat losses from the combustion chamber to the cylinder walls and then to the cooling system.

**Snapshot 2**: Expansion

- The snapshot is taken at 90$^o$ (crankshaft angle) after TDC. The kinematic position of the system is ideal for maximum torque generation. However the cylinder pressure in much less than the maximum combustion pressure since the volume is almost 3 times higher than the initial volume of combustion. Also the combustion gasses have already lost some of their enthalpy due to heat transfer phenomena with the cylinder walls since the expansion process is not Adiabatic (as the theory states).
- The combustion process is not yet finished and some molecules of fuel are still being combusted. This phenomenon of combustion process elongation is more apparent when the engine is burning lean air-fuel mixtures (in order to achieve fuel economy when the output demand is low). The result of this faint scattered combustion is the production and emission of CO due to incomplete combustion and unburned HC sometimes apparent in the form of soot.
- The soot (solid carbon), which is formed from the incomplete combustion usually, is trapped inside the cylinder and is being attached at the combustion chamber walls, the exhaust valve poppet and the spark plug electrodes. Those carbon particles are not good heat conductors, therefore they cannot dispense the heat of the repeated combustions in the chamber. The result of this local heat-insulating phenomenon is the creation of “hot spots” inside the combustion chamber, which are able to pre-ignite the air-fuel mixture before the normal spark plug ignition. Due to the pre-ignition (commonly known as knocking) the power output of the engine is deteriorated and severe mechanical problems may occur (push rod bending, crankshaft cracking e.t.c)

**Snapshot 3&4**: Exhaust

- The piston is near the BDC (almost 180$^o$ after the TDC) and the exhaust valves are opening. The exhaust gasses rush out of the cylinder and the pressure is rapidly reduced to the atmospheric pressure.
- Due to the fact that combustion and expansion processes are highly inefficient, the exhaust gasses possess high enthalpy, which is apparent in the form of high exhaust gas temperature. A more efficient combustion and more efficient mechanical linkage (instead of the traditional crankshaft) would reduce the temperature of the exhaust gasses.
- The exhaust gasses flow around the exhaust valves and heat them up. The hot exhaust valves are crucial points for pre-ignition (knocking) during the engine operation. This danger is more apparent in the case of hydrogen combustion since hydrogen is more easily ignited than gasoline. A commercially used solution is the creation of hollow exhaust valves, which are filled with solid Natrium, which serves as coolant.
- At the second stage of the exhaust phase, the piston in moving upwards since the angle of the crankshaft is more than 180$^o$ after TDC. The piston now pushes the exhaust gasses out of the cylinder, which means that it consumes energy. In addition to that this upward motion is characterised by very high friction due to the piston-slapping phenomenon. Due to the angle between the rod and the motion of the piston, one side of the piston is pushed towards the cylinder wall, while in the same time the piston tries to rotate around is piston pin. This awkward motion causes high friction. The engine manufacturers try to reduce this phenomenon by forming lumps at the piston body or my offsetting the whole cylinder (in order to reduce the rod-cylinder angle).

**Snapshot 5**: Overlap

- This is one of the most crucial, beneficial and in the same time problematic phases of the engine operation. It is the end of the exhaust phase and the beginning of the intake phase and the piston is just some degrees of crankshaft angle before the TDC. At this point (and against the theoretical thermodynamic description) all the valves of the engine are partly open. The exhaust valves are closing since the exhaust phase is ending, but also the intake valves are opening (before TDC) in order to serve the double cause of forced exhaust and forced intake. This means that the high speed exhaust gas flow, which reduces the cylinder pressure (lower than ambient pressure) due to gas momentum, “sucks” fresh air-fuel mixture from the intake plenum creating a form of mild “supercharging”. In the same time the fresh mixture that enters into the cylinder is characterised by high speed and swirling motion. This flow pattern is created from specially calculated and designed air intake parts, and forces the remaining exhaust gasses out of the engine.

- Overlap is very helpful for the engine operation since it assures a successful combustion (of the next cycle) without exhaust gas remains. However when it comes to emissions, the overlap technique is facing major problems. No matter how well calculated the engine parts are, it is almost impossible to achieve a full elimination of the exhaust gasses without having losses of fresh air-fuel mixture to the exhaust pipe. And if this is not a problem at the performance engines where the absolute power is more important than the emissions' reduction, this is not the case in commercial engine market. The solutions to this problem are either extremely thorough CFD analysis of the engine parts and Exhaust Gas Recirculation (EGR) or overlap elimination.

**Snapshot 6&7**: Intake

- The piston now moves rapidly downwards creating a vacuum in the combustion chamber. This suction effect causes the rapid movement of the air-fuel mixture from the intake plenum towards the cylinder. The mixture rushes through the inlet valve passage and is forced (due to geometric conditions) to a high speed swirling motion. This motion homogenizes the mixture and achieves better combustibility of the fuel do to higher atomisation.
- Modern diesel and gasoline engines are thoroughly studied with the help of CFD programs and are able to achieve special flow patterns during the intake phase. A characteristic example is the FSI combustion, where the intake flow pattern causes stratification of the mixture in the combustion chamber, with the higher fuel concentration in the vicinity of the spark plug electrodes. FSI combustion achieves successful and complete combustion of very lean fuel-air mixtures.

**Snapshot 8**: Delayed Compression

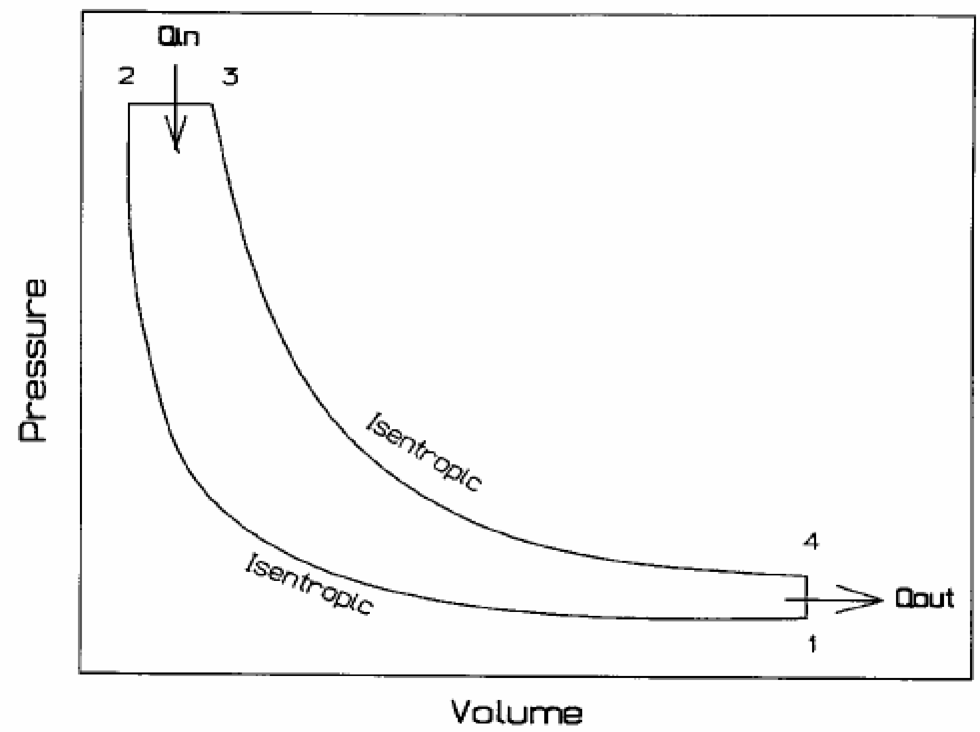
- The piston passes the BDC and starts moving towards TDC to perform the compression phase. However for some degrees of crankshaft rotation after the BDC, the intake valves remain open preventing the initiation of the compression. Although it seems false, this technique uses the momentum of the incoming air-fuel mixture in order to increase the cylinder fill factor.

**Snapshot 9**: Compression

- All the valves are now closed and the piston moves upward compressing the air-fuel mixture. The temperature of the mixture is rising due to the pressure increase and some degrees before TDC the sparkplug ignites the mixture. The advance at the ignition timing is very important in order to utilize the maximum amount of thermal energy of the combustion, since there is a small delay between the ignition and the combustion. This delay is caused from the flame propagation and an innovative solution for this problem in the Hydrogen Enhanced Combustion.

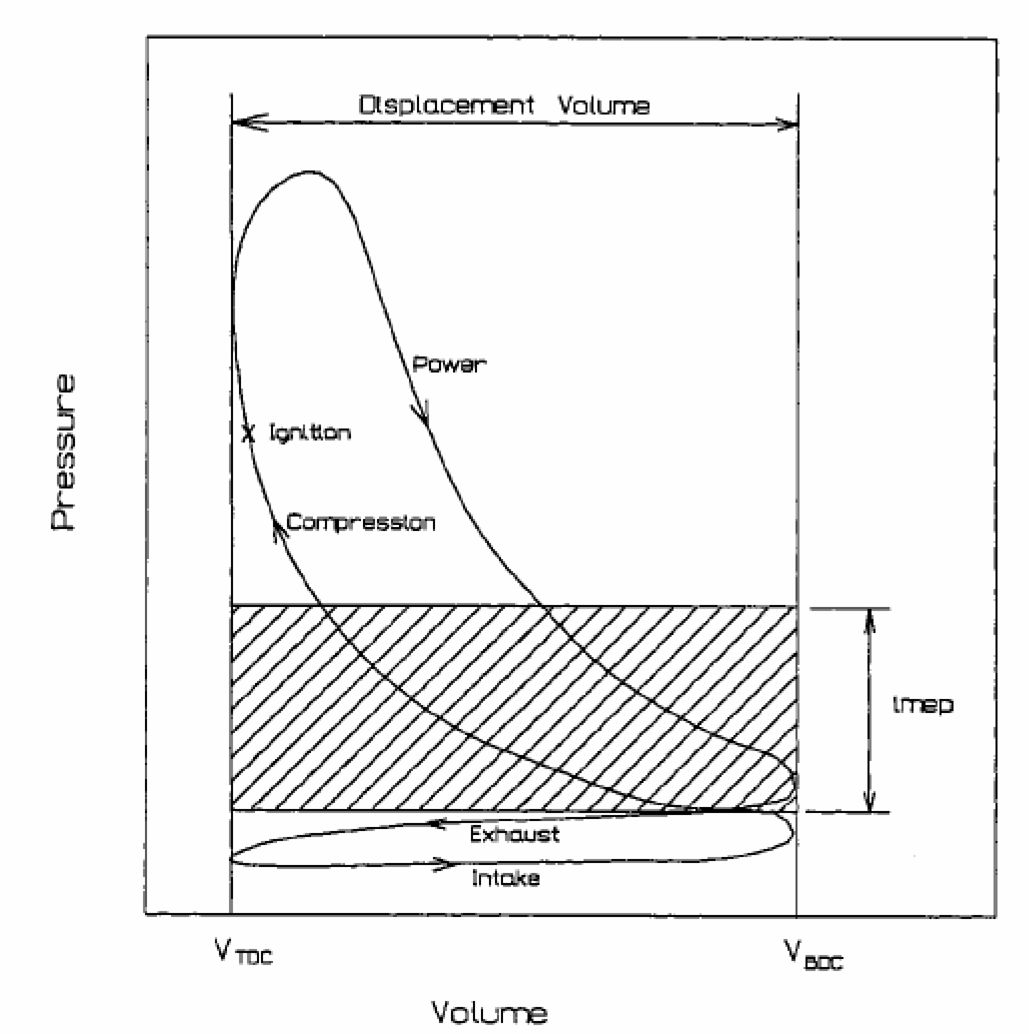
**Appendix Ib: "The Diesel Cycle"**
Compression Ignition – Internal Combustion Engine

The fundamental characteristics of the diesel engines are similar to the gasoline spark ignition engines, even though the thermodynamic operation of those engines is totally different. Due to the resemblance of the physical engine parts of the Diesel and Otto engines and due to space restrictions for the Appendix, the operational details of the diesel engines will not be discussed in detail. The informed reader should be familiar with the fundamentals of diesel combustion and just for additional reference the diesel thermodynamic cycle is provided below.




*The Pressure – Volume diagram of the Diesel cycle* [6]

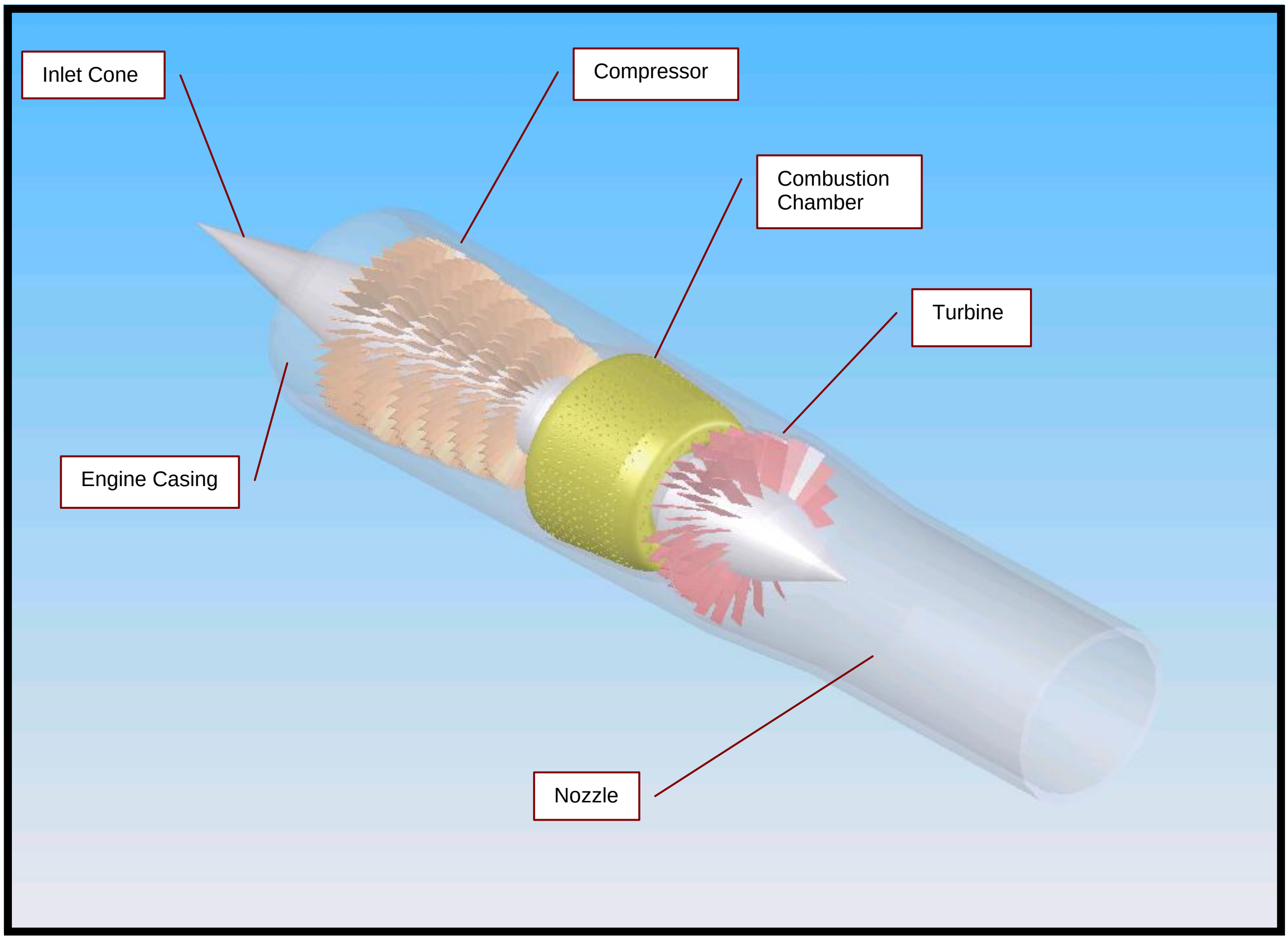
Finally, what should be noted is that both Otto and Diesel engines do not operate in reality in accordance to the theoretical thermodynamic cycles. The following diagram shows the actual cycle of an internal combustion engine which can be either Spark Ignition (Otto) or Compression Ignition (Diesel).




*The actual Pressure – Volume diagram of a Diesel or an Otto engine* [6]

## Appendix II: "The Brayton Cycle"

Gas Turbine Operation

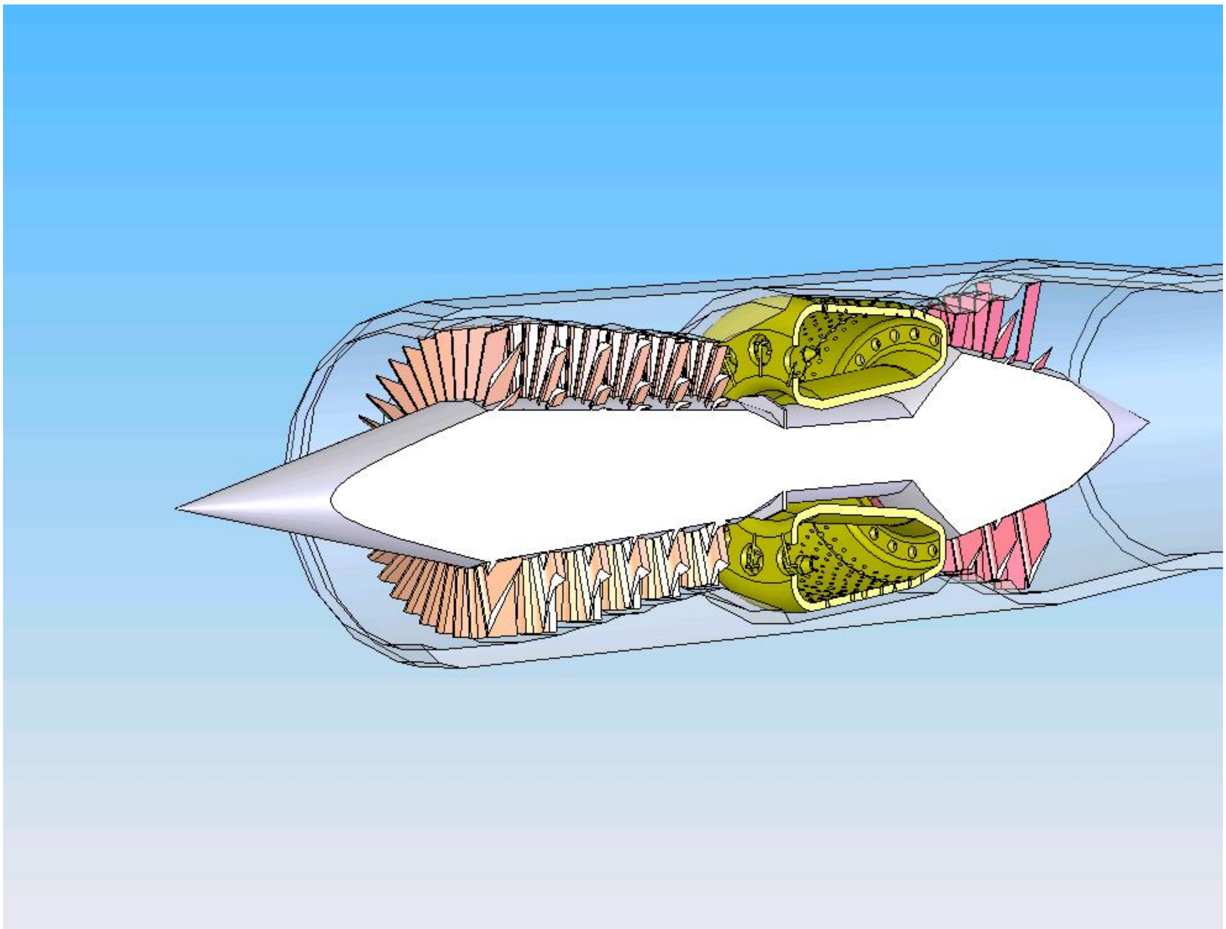



### Basic Part Description

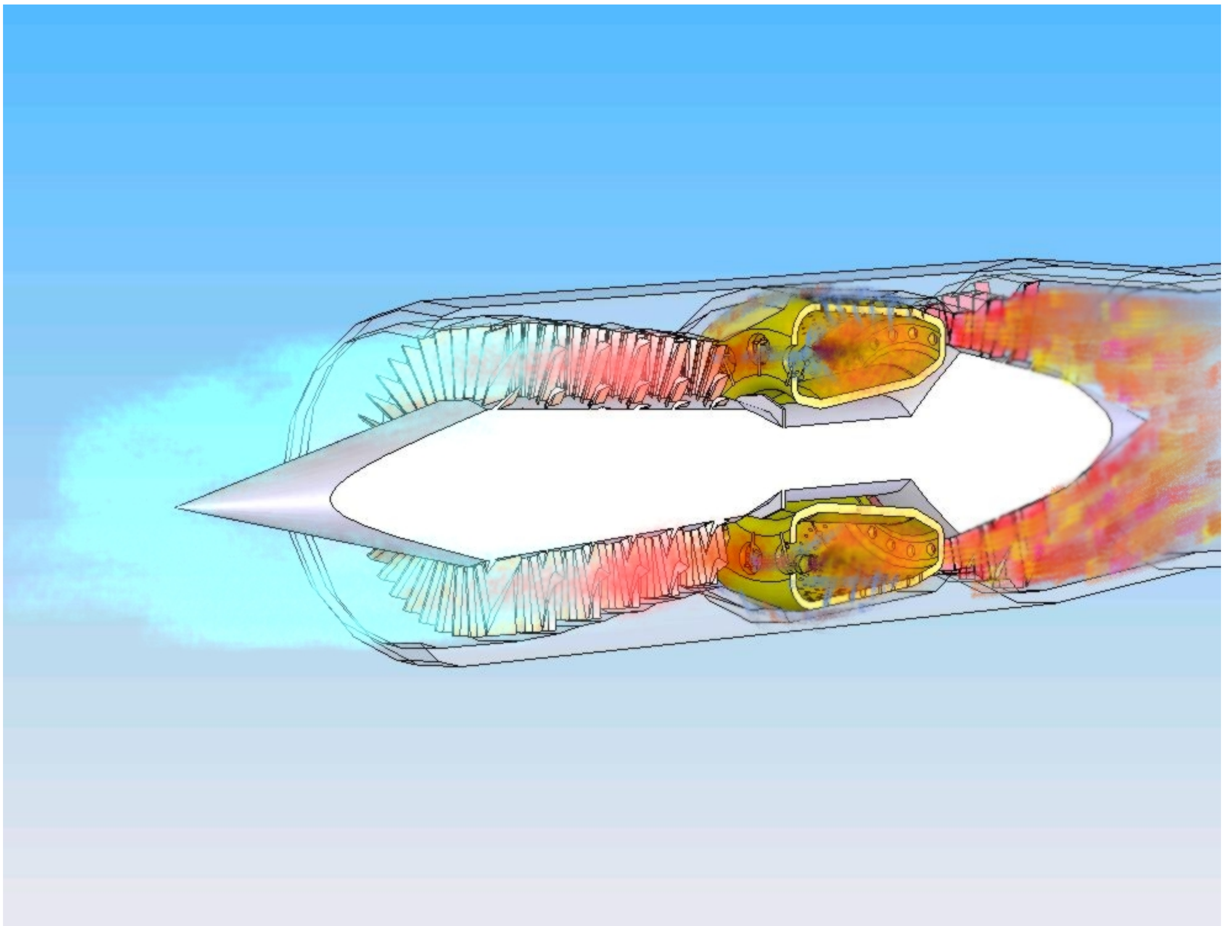
- **Inlet Cone**: The conical formation at the front of the engine. It is made of composite materials or light alloys and its purpose is to create normal or oblique shocks at the incoming airflow in order to reduce its speed.
- **Engine Casing**: The cylindrical cover of the engine's rotating shaft. It is usually made from actively cooled titanium alloys or Inconel and aluminum and serves both as the rotor supporting structure and as flow guiding apparatus.
- **Compressor**: The axial compressor, which comprises of one or more compressor stages increases the pressure of the incoming flow. The compressor blades are usually actively cooled with internal cavities and are made of titanium alloys.
- **Combustion Chamber**: Toroidal structure made of titanium alloy or ceramic material, equipped with numerous holes. The air stream enters inside the combustion chamber from the front and peripheral holes and mixes with the sprayed fuel. After the combustion the expanded exhaust gasses exit the combustion chamber from the rear holes. The combustion

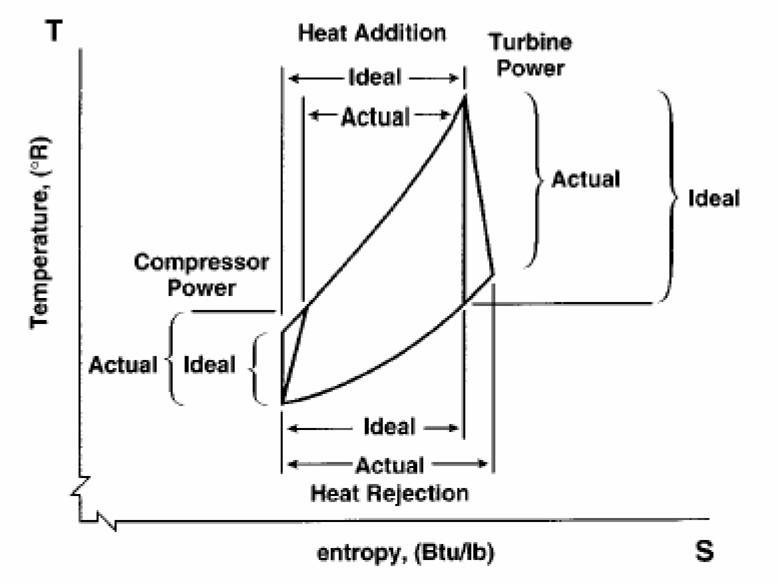
chamber walls are actively insulated and cooled from the air stream that flows around them, therefore the design of this engine part is extremely demanding and requires well established know how.

- **Turbine**: Rigidly connected to the compressor's shaft, comprises of many airfoil type high precision blades which are made of heat resistant titanium alloys or hi-tech ceramic materials. It converts the kinetic energy of the exhaust gasses to rotational motion and drives the compressor.
- **Nozzle**: Can be moving or non-moving, divergent – convergent or just divergent depending on the operation profile of the engine. It is made of heat resistant sheet metal and its purpose is to create the engine's thrust which will lead to the forward motion of the host vehicle (NOTE: A very big portion of the thrust also comes from the outlet cone).



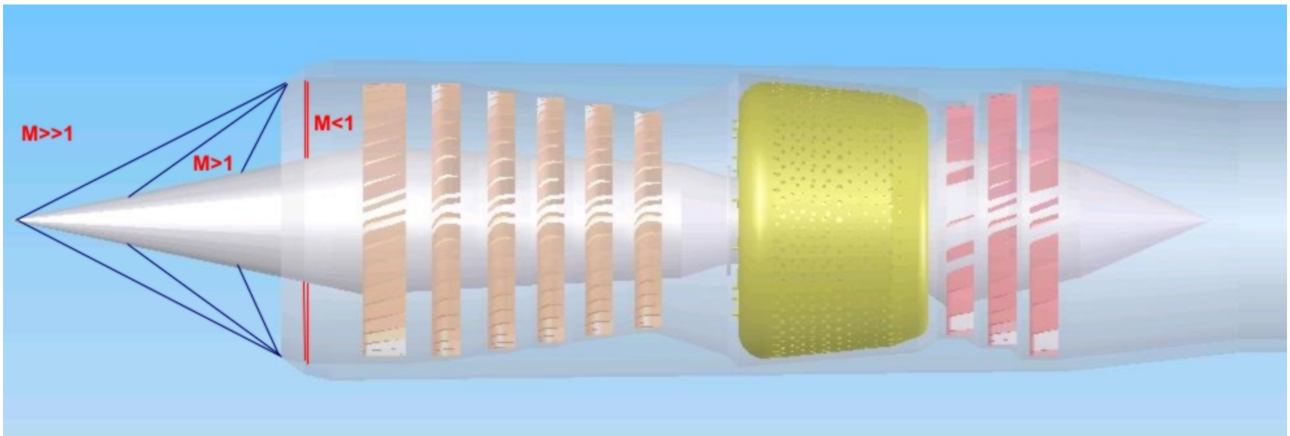
## The Operation of the Gas Turbine

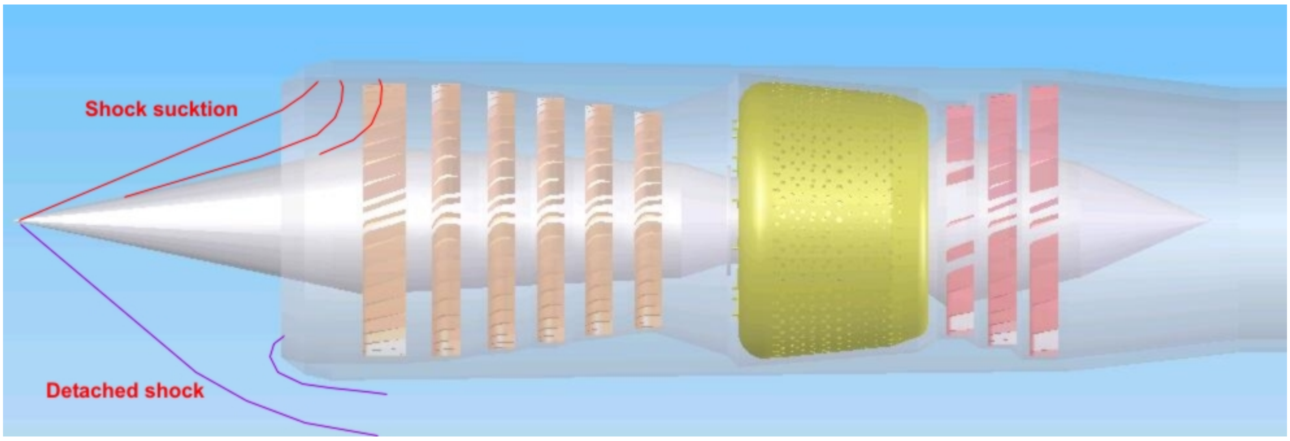





*The Temperature – Entropy diagram (actual & theoretical) of the Gas Turbine* [6]

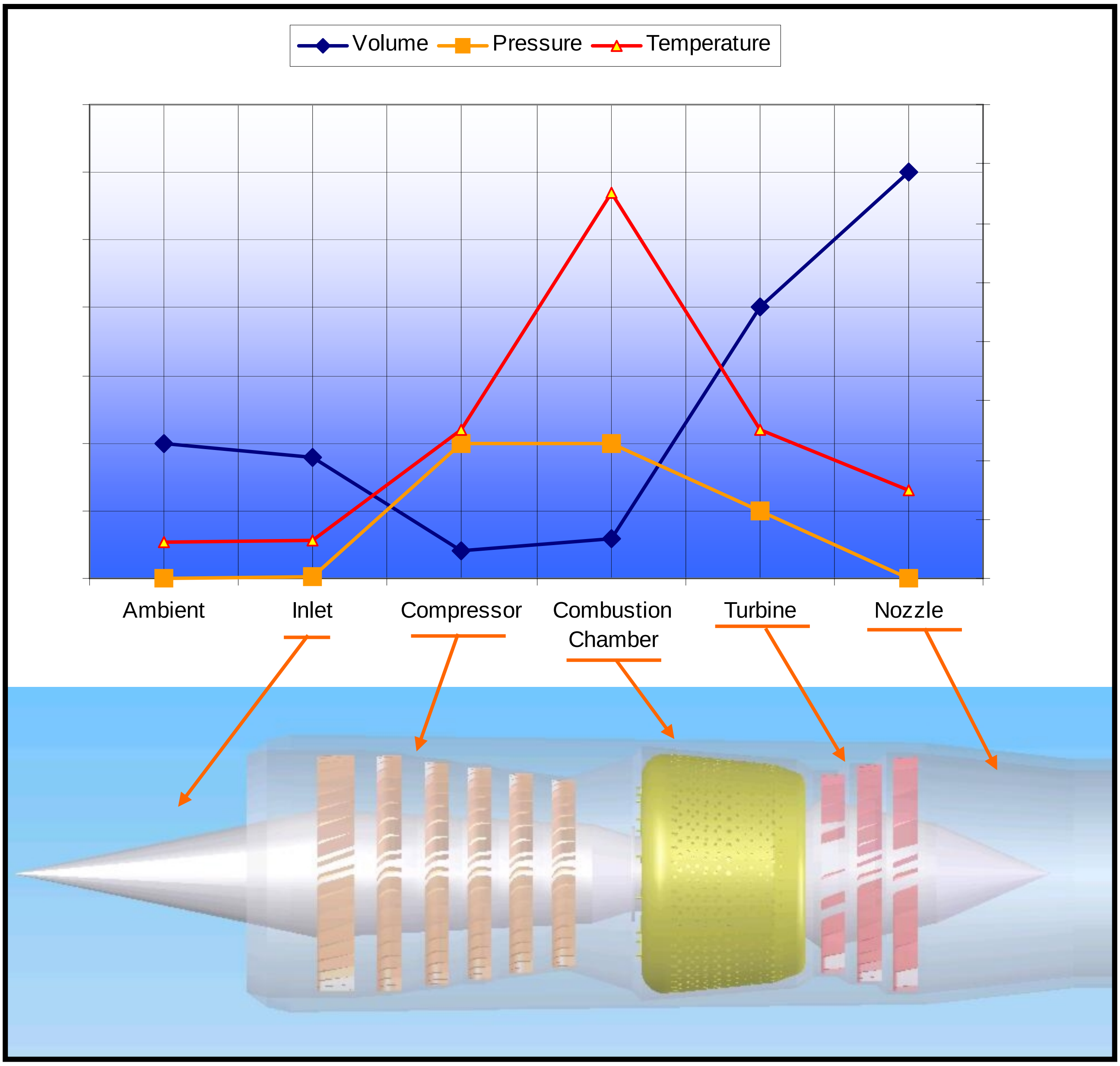
1. **Air Intake:** Supposing that the vehicle equipped with the turbine is moving, the relative velocity of the incoming air stream is high. In case of supersonic velocity, the inlet cone causes one or more oblique shocks at the air stream, which reduce the stream's velocity to low supersonic speeds. Then, just before the compressor, a final normal shock is created (caused by a specially designed feature at the end of the cone) and the airflow speed becomes subsonic. One of the most crucial parts of this deceleration procedure is the precise placement of the shock points so that the final flow that enters the engine is almost of equal speed at about the same point. The following images show a graphic example of an ideal shock operation and also the cases of shock suction and detached shock. In the first case the engine operates ideally and the airflow speed reduction leads to an increase of the static pressure in front of the compressor (which enhances the engine's performance), but in the case of shock suction (also know as engine "buzzing") the shock oscillates in the compressor area causing severe vibrations that in the worst case can lead to combustion flame extinguish. Detached shock is not so critical but causes great drag increase and reduces the active airflow with negative results at the engine's efficiency.



2. **Compressor:** The multistage axial compressor is one of the most important parts of the gas turbine. Its blades should withstand enormous centrifugal forces during the engine operation, as well as very high temperatures, vibrations and collisions with any small particles or water contained at the air stream. The blades are airfoil shaped and cooperate with the stator blades (also called stator vanes…not visible in the images) in order to achieve a pressure increase of several bar. In many aircraft engines the front stage of the compressor serves as a fan, which leads a portion of the inlet air, to the by-pass passage of the engine in order to increase the air flow rate of the engine and the net thrust at high subsonic or transonic speeds. However the description and analysis of the different engine configurations (turbojet, hi by-pass turbofan, low by-pass turbofan e.t.c) is out of the scope of the present document.
3. **Combustion chamber**: The combustion chamber is stationary and attached to the turbine casing. The high temperature-high pressure air from the compressor enters the combustion chamber through the numerous holes and slots at the front "face" but also at the circumference of the chamber. The swirling air mixes with a high-pressure fuel (spayed liquid or gas) and ignites. The initial ignition is caused from an electric igniter plug but when the engine reaches the operational speed and temperature conditions, the combustion is self-sustainable. The temperature of the airflow increases rapidly and the exhaust gasses expand and find their way out of the chamber through the holes at the rear part of the chamber.
4. **Turbine**: The high-pressure, high temperature exhaust gasses coming out of the combustion chamber go through the stator "turbine vanes" where they acquire the appropriate direction in order to "engage" the turbine blade with an ideal angle. The turbine blades are specially designed in order to convert the motion of the expanding exhaust gasses to rotational motion of the shaft. They are also shaped like airfoils but with different profile than the compressor blades and made of different metal alloy since the operational conditions of the turbine blades are really severe. Therefore the construction of the turbine parts is a very demanding task not only regarding the design aspects, but also in the material selection point of view. When the exhaust gasses pass all the way through the turbine, they come out at the back of the turbine where they have significantly lower pressure and temperature. A big portion of their enthalpy is consumed in order to maintain the rotational speed of the compressor – turbine shaft against the friction and pumping losses. The rest of the energetic potential of the gasses is transformed to kinetic energy (the result of which is thrust) at the engine outlet cone and nozzle area.

The following diagram shows the general behavior of each of the main engine parts according to the Volume, the Temperature and the Pressure. It is obvious that the inlet cone and the compressor increase the pressure and the temperature of the airflow, while the combustion chamber increases the temperature under constant pressure. The pressure and the temperature drop again at the turbine and the exhaust nozzle since the energy is extracted from the gasses and is transformed to rotational and translational motion (or only rotational motion at the stationary gas turbines).



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# Images

[a] *All the 3D Drawings and Cut-Views were created with SolidWorks 2004 and processed with Corel 12*

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[c] *All the other images are acquired from the articles described in Bibliography.*