EH2TA

Education in Hydrogen Technologies Area

HYDROGEN FOR INTERNAL COMBUSTION ENGINES

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CONTENT

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INTRODUCTION

The ongoing energy debate, due to the environmental destruction that can be directly linked to the use of known fossil fuels, has led to us being forced to find new sources of energy. All fossil fuels such as all oil and natural gas that come from the ground contain carbon, which turns into carbon dioxide when burned. Everything that contains carbon that we then burn in different ways, leads to us not reducing carbon dioxide emissions, but in most cases increasing them.

With an increasing population globally, the need for means of transportation for private individuals, commercial vehicles, shipping and aircraft grows. This increases the need for fuel for this growing fleet. In other words, with a larger global population there is also an increasing need for fuel. Recently, it has become increasingly apparent that our way of life affects the climate. In some parts of the world, climate change leads to droughts and huge forest fires while other parts are hit by huge rainstorms that lead to floods. Research is going on in several places in the world and new technologies for all these means of transport are at the top of the agenda. Alternative fuels have been researched and some are already in use, others are still more or less in project stages. Electrification of different types of vehicles is something we are seeing more and more, these vehicles are still relatively expensive and may not yet be accessible to all the public, the range of these vehicles is also still not quite like that of traditional petrol and diesel vehicles. Furthermore, the production of electricity is also not always solved in a completely environmentally friendly way. Other fuels that can be mentioned are, biofuels, which are residual products from our household waste and agriculture. Alcohol or ethanol is a fuel that has been around for quite some time as a supplement to gasoline-powered cars. Rapeseed oil is also an alternative to fossil fuels. None of these alternative fuels increase carbon dioxide emissions but keep them at a neutral level. They are part of the natural cycle.

Hydrogen has been researched during various periods in our world history. One relevant question is why research seems to have progressed at certain times and then slowed down only to later start up again. Hydrogen vehicles that run on so-called fuel cells are starting to appear in some parts of the world, though, not as common as passenger cars in Sweden. However, in public transportation, such as bus traffic you see them appearing a little here and there. Even today, you can't go in and buy a car or truck with an internal combustion engine that runs on hydrogen, but some manufacturers are close to a finished vehicle.

1 HISTORY

This chapter briefly tells the history of hydrogen, from the 18th century up to this day. You will learn about some early inventions of hydrogen combustion engines and ideas that are still relevant in hydrogen development today.

KEY WORDS:

history of hydrogen, automobile, Rivaz.

STUDY QUESTIONS

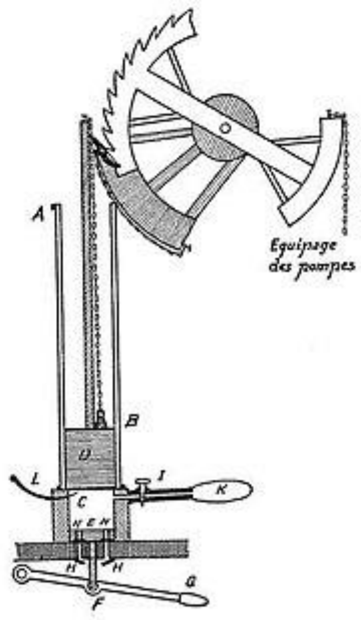
1. Who was the man that was first with a functional internal combustion engine?
2. What forced the rapid change in fuel use in Leningrad 1941?
3. In what way was 1966 a successful year regarding hydrogen development?

We know that way back in 1700 there were attempts to invent self-moving carriages, without using a horse as a transportation method. The Frenchman Cugnot constructed a carriage powered by a steam engine, and its purpose was to carry a cannon for the army. This self-moving carriage was given the name automobile from the Greek word autos which means self and the Latin word mobilis which means moving. Unfortunately, it all ended very abruptly. Cugnot's carriage ran into a wall and was totally destroyed.

When reading history about engines, you notice that Nicolaus Otto was the inventor of, supposedly, the first engine with an internal combustion chamber. The Diesel engine was invented by Rudolf Diesel; he also named the fuel. All this took place sometime in the middle 1800's, unfortunately it's hard to be precise due to when the invention was patented. Otto was first with the modern internal combustion chamber engine in 1876, but even before that, Etienne Lenoir successfully invented an internal combustion chamber engine for commercial use circa 1860. With all this in mind, a gentleman called Francois Isaac de Rivaz was even before Étienne, Rudolf and Otto.[1] He was born in France in

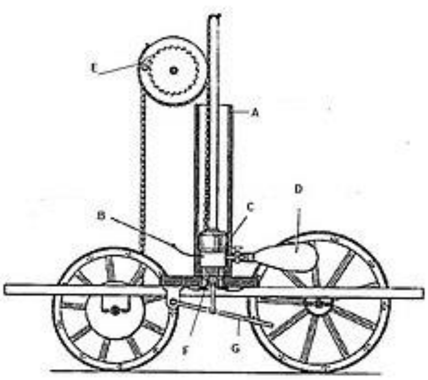
[1](Wikipedia, 2019)

1752 and later moved to Switzerland where he became an inventor and politician. Early in the 1800's, Francois had a primitive engine ready.



First version of de Rivaz's engine (Image 1)

A little later he also had a horseless carriage; where he put in another one of his engines, this was claimed to be the World's first internal combustion chamber engine to power an automobile. And circa 1809, he travelled around the Lake Geneva.

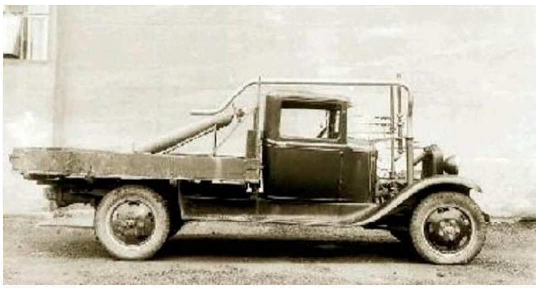


One of Rivaz's early wagons (Image 2)

But Francois was probably too early for his time, as few believed in him, and claimed that his invention would never be able to compete with the steam engines. But what Francois used for fuel was not diesel or gasoline, he used hydrogen.

We move half a century forward, 1860, and another inventor, a Frenchman by the name Etienne Lenoir, developed the three-wheeler Hippomobile. Lenoir's Hippomobile was powered by a one cylinder two- stroke engine. The hydrogen was produced by electrolyzing water, and the gas was fed to the engine.

The next hydrogen car in line was invented in Norway in 1933, when Norway's Norsk Hydro power company converted a small truck. The truck was equipped with an ammonia reformer that produced hydrogen which was then fed to the internal combustion chamber engine.



Norway's First hydrogen converted truck (Image 3)

In 1941 when the World was at war, the German Nazi army had surrounded Leningrad, which led to slowly running out of gasoline for the military vehicles. The lack of gasoline compelled "new" inventions. Therefore, Russia's Boris Shelishch, converted 200 GAZ-AA trucks to run on hydrogen, it showed that they burned cleaner and ran longer than those which had run on gasoline. For some reason all the detailed documents regarding hydrogen as a fuel alternative have mysteriously gone missing after World War Two, and they are still missing.

1959 Harry Karl Ihrig modified an Allis-Chalmers farm tractor to create the first fuel cell vehicle in history. Fuel cells are not going to be described here, just pointing out that there was a continuously parallel development in both these paths for alternatives for fossil fuel this early in history. [2]

[2](National Museum of American History, n.d.)

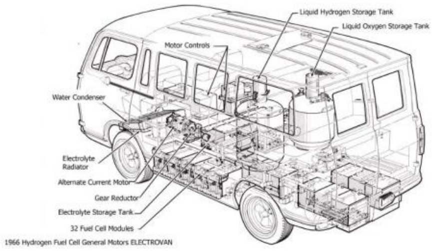
Harry Karls Ihring fuel cell tractor (Image 4)

1966 was a successful year for hydrogen both when it comes to internal combustion chamber engines and hydrogen for fuel cell vehicles. Roger Billings gave new light to the hydrogen fuel and converted a regular Ford model-A truck to run on hydrogen fuel in its normal gasoline engine.[3]

Roger Billings hydrogen converted modell A, 1966 (Image 5)

The same year General Motors created the GM Electrovan fuel cell vehicle, which is recognized by many to be the first fuel cell vehicle passenger automobile of record.

[3]Roger Billings (Billings, 2013)



GM's first fuel cell van from 1966 (Image 6)

Since then the development for both running hydrogen in internal combustion chamber engines and fuel cell vehicles have advanced forward.

2 THE HYDROGEN GAS

This chapter briefly describes hydrogen gas and one of the manufacturing processes without an environmental footprint and presents different types of hydrogen driven vehicles. The production of hydrogen gas is further explained in a different module.

KEYWORDS:

hydrogen gas production, weight ratio, hydrogen driven vessels, electrofuel.

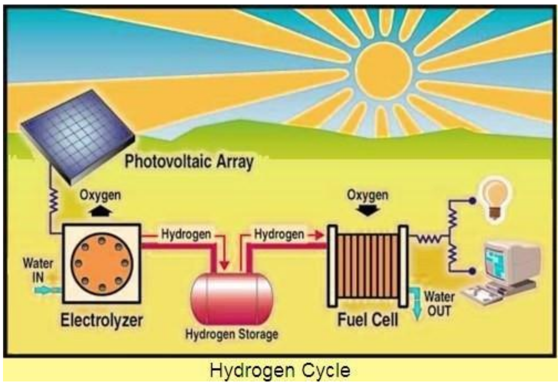
STUDY QUESTIONS

1. What's the weight ratio of air versus hydrogen gas?
2. Give an example of where hydrogen can be refined from?
3. What kind of vehicles/vessels could be possible for the use of hydrogen?

Hydrogen gas is the lightest of all the elements in the universe, it is about 14 times lighter than air and this means that the hydrogen spreads very quickly in the event of a leak. Hydrogen consists of two hydrogen atoms and therefore has the chemical designation H_2. It is colorless, odorless, non-toxic and even then highly flammable. Hydrogen is the most abundant chemical substance in the universe and makes up approximately 75% of all normal matter. Down on earth, it is significantly rarer, only 0.15% of the mass, it is found bound in various forms of matter, for example in water, H_2O.

Production of hydrogen

The first documented time that hydrogen was produced artificially was at the beginning of the 16th century with acids that reacted on various metals. Today, there are a number of ways to produce hydrogen, the different ways affect the environment more or less, and work is constantly being done to try to produce it as green as possible. What we know today that is best for the environment is if you can use solar energy or wind turbines, but even these methods have a certain negative effect on the environment.[4]



Hydrogen produced by solar energy (Image 7)

Here, only one of the ways will be explained in a very simplified way. You can say that it is done in such a way that you separate the oxygen and the hydrogen from each other. This is done by charging the water with electricity. Salt water is an advantage to use because it conducts electricity better, it can also be called splitting the water. What then happens is that oxygen and hydrogen gas come out, but separated from each other. In this chapter, we will not delve too much into how the production itself goes beyond the fact that it can actually be done at home, if you have the right equipment. At the same time, you have to remember that it is a very flammable gas you are dealing with.[5]

[4]Kumar (2016)

[5](Office of Energy Efficiency & Renewable Energy, 2019)

Different types of vehicles

Development has come a long way and the use of hydrogen in all possible types of vehicles can be seen today. Most of the major vehicle manufacturers around the world are testing their cars where they have developed engines that run on hydrogen only, or rather modified them to run on only hydrogen. What should be added here is that development moves at such a high speed that it is difficult to be completely up-to-date on the subject, and what is written here today may be old tomorrow. Buses have been successfully driven with hydrogen with traditional combustion engines in various parts of the world.

A bus powered by hydrogen with a it's conventional engine, Keyou is the company behind it (Image 8)

One of the issues is that it is not completely zero emissions, because the carbon oxide content, CO, and carbon dioxide content, CO_2, is almost non-existent. But, on the other hand, the nitrogen oxide content, NOx, you struggle with in different ways to bring it down to an acceptable level. In a combustion process, air is used and the nitrogen in the air is then converted into nitrogen oxide, which means that these vehicles do not meet the requirements to be classified as a vehicle with zero emissions, but research continues to succeed in this too. We will come to this later and explain how to work with this. Also, within the other sector of heavy vehicles, research is being conducted into using hydrogen as fuel for the already existing internal combustion engines. Long-distance traders that have been completely dependent on fossil fuels soon won't have to be.

Already today, in theory, you can drive completely fossil-free and only use hydrogen as fuel. The engines have proven to work at least as well on hydrogen as on diesel, and the engine output, torque and fuel efficiency are just as good as before, some developing companies in the fuel injection fields even claim that their product puts out higher figures on both the effect and the torque. Furthermore, the problems that electric car owners have with regard to charging stations and the time it takes to charge are completely avoided, because time is precious in this transport sector.

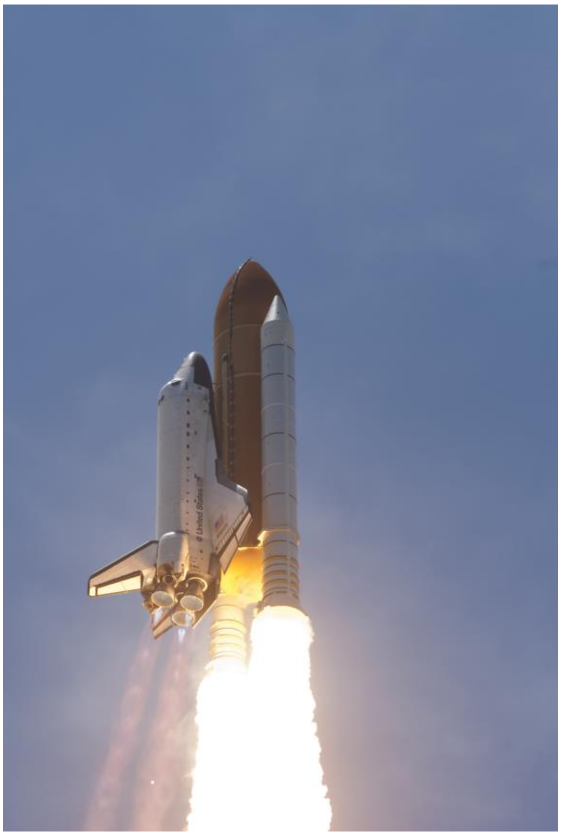
In shipping, it is the same development, in addition, here you will reach an even greater environmental goal since there are no restrictions on the fuel that is used, there is also no purification of what comes out, several shipping companies are already testing hydrogen today.

Aviation is also developing alternative sources of propulsion for aircrafts, and one alternative is hydrogen. It has recently made successful attempts at flights with hydrogen, it was in this case with a mixture of another fuel called electrofuel. Electrofuel is a collective name for carbon-containing fuels produced by electricity as the main energy source. The carbon atoms in the fuel come from carbon dioxide collected from the air, the sea or from fuel gasses from power plants, you can call it a form of carbon dioxide recycling.

Different types of aviation vessel's are tested (Image 9)

Space shuttles have also used hydrogen but then in liquid form, together with oxygen also in liquid form. The tanks were 15 stories high and held 530,000 litters of liquid oxygen and 1.5 million litters of liquid hydrogen. These are gasified in a combustion chamber and provide propulsion for the rocket. All this amount of fuel was used up in 8 minutes and 20 seconds.[6]

[6](KSC, n.d.)



A space shuttle loaded with hydrogen and oxygen (Image 10)

In short, it can be stated that the fuel hydrogen can definitely be used in more or less all types of vehicles and crafts. However, it seems that development has not really taken off in the passenger car sector, at least not yet today, but there are prototypes that appear here and there from various manufacturers around the World.

3 REFUELING

In the following chapter you will learn about the risks regarding refuelling hydrogen. You will also learn about the advantages compared to recharging electric vehicles and the future of hydrogen fuel and refuelling.

KEYWORDS:

refuelling, potential risks, petrol and diesel vs. hydrogen.

STUDY QUESTIONS

1. How is it an advantage to refuelling with hydrogen compared to charging an electric vehicle?
2. Why is the hydrogen gas pressurized to such high figures?
3. What could be a safety risk when refuelling hydrogen?

Refuelling today, at the time of writing, May 2022, can be done at five locations in Sweden, and in Europe there are a total of approx. 230 stations where you can fill up with hydrogen. Germany leads the way with its 101 stations, followed by France with 41 stations, Great Britain has 19, Switzerland 12 and the Netherlands 11. The lack of filling stations can only be hypothesized to be currently hampering the development to switch to hydrogen, but development is also underway here forward.[7]

It's clear that there needs to be a lot more gas stations providing hydrogen to make the development at a good pace (Image 11).

The big advantage with filling up hydrogen compared to charging an electric car is huge in terms of time, it doesn't take longer than filling up a petrol or diesel car, i.e. about 2-5 minutes depending on the size of the tank. Charging an electric car at home takes about 8-12 hours, at a charging station with a so-called fast charger with a higher voltage you can shorten it to about 20 minutes. But, then you have not reached a full charge on the batteries, only about 80%.

[7](Autovista SE, n.d.)

The refuelling of hydrogen is done from a pressure tank at the station into the car, where it is also pressurized. The pressure in a truck tank is 350 bar, in a car it is 700 bar. The gas is pressurized to accommodate more, but as mentioned earlier there is a constant development, which means that those figures already might have changed.

The gas filling nozzle is very similar to the ones used in other gasses for vehicles (Image 12).

The risk assessment that an accident could happen when refuelling, will be presented in a different module that concentrates on just that matter "Charging stations". But due to the high pressure in the tanks, there is a potential risk of leakage, as the gas is many times lighter than air. The pressure will increase, and since refuelling usually takes place outdoors, it increases quickly and mixes with the air . If, on the other hand, it gets stuck under a roof and some form of thermal ignition occurs, there is a great risk of a rapid fire. It is therefore of great importance that there are sensors that can give an early warning of gas leaks and that the premises in which leaks may occur are equipped so that ventilation devices can be quickly activated.

3.1 REFUELING AT YOUR OWN RESIDENCE

Refuelling at your own residence could be possible, that question is really about what our decision-makers come up with, but it will certainly be feasible. We can already "refuel" our own electric car, as well as other people's. So, with the right equipment, if we want to be environmentally friendly, i.e. green electricity, which means solar cells on the roof or a wind turbine, you can produce your own hydrogen, it "just" needs to be compressed to have it in a vehicle.

Here's an fuel station for home use developed by Honda, this one here also provide the household with electricity by a fuel cell

(Image 13)

3.2 PETROL AND DIESEL

For nearly 150 years, we have more or less relied on petrol and diesel to propel our vehicles and vessels on roads, in water and in the air. There were actually also other options over a hundred years ago that were probably so close to succeeding instead. Electricity, for example, was far ahead, all sorts of different types of electric vehicles existed over 100 years ago. Speed records of over 200 km/h with electric cars were set on the high-speed tracks at the beginning of the last century in America. Steam-powered vehicles were also an option, not only trains but also passenger cars. But then what was it that made the petrol and the diesel the ones that won the game? You will not be able to get any answers to these questions. Another relevant question is; what would the environment have looked like today if other alternatives had been found then?

Would we have had the global temperature increase that we have today if we had invested in something else instead of diesel and petrol? But the fact is that when the car and the combustion engine made their entrance at the beginning of the last century, it was considered a good environmental investment, the big cities around the world had big problems with all the horses inside the cities that pulled wagons with both goods and people. A big problem was that the horses also had to fulfil their natural needs both number 1 and number 2 and of course this was done everywhere in the middle of the city.

This is what the cities looked like in the beginning of the last century, the smell must have been distinct (Image 14).

In addition, this was something that the horses did 24 hours a day, regardless of whether they were in use or not, unlike the car, when it was not being driven, of course you just turned it off, and then did not consume any gasoline or diesel at all, it then released nor emit any exhaust gasses.

The hydrogen, on the other hand, at this time did not have a major field of use, in any case it was no longer relevant as propulsion for vehicles on the roads, at least not for general use, on the research level there was an ongoing process. What they came up with instead was that you could use the light gas to make other crafts fly, the Zeppelin. Actually, these were intended for helium and had been used to fly across the Atlantic. Ferdinand Adolf Heinrich Von Zeppelin, who was born in Germany in the early 19th century, was the man behind these crafts.[8] Since America at that time was the world leader in helium production but at the same time did not allow export, the craft was filled with hydrogen. Unfortunately, together with air or oxygen it becomes very flammable. In 1937 during a flight with the Zeppelin Hindenburg in America when landing it suddenly caught fire. It is believed that it was struck by lightning but it is still not clear today if this was what triggered the accident, or if it was a sabotage. In any case the whole thing was caught on film. The craft quickly went down to the ground and the progress of the fire was very fast. 35 people on board and one on the ground died. Whether or not this accident may have led to great scepticism about hydrogen gas or not, one can only speculate, but the strong disaster film probably had a great impact on the use of the gas. In any case, the Hindenburg disaster marked the end of the era of large airships, for the time.[9]

[8](This Day in Aviation, 2023)

[9].(SO-rummet, 2022)

The luxurious airship Hindenburg caught on camera when the disaster took place 1937, 36 people were killed (Image 15)

Today the development in the field of large airships has resumed, but if they are going to be inflated with hydrogen or helium is still not clear. The reason for the renewed interest is that airships are much better for the environment than regular airplanes.

4 THE FOUR-STROKE PRINCIPLE IN AN OTTO ENGINE AND DIESEL ENGINE

This chapter explains the principles behind two types of engines, the Otto engine and the Diesel engine, which could be used with hydrogen as a fuel. You will also learn more about the four-stroke principle related to these engines.

KEYWORDS:

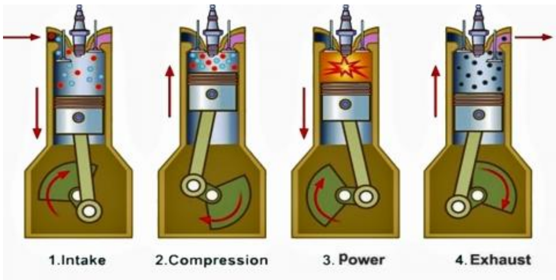
Otto engine, Diesel engine, the four-stroke principle.

STUDY QUESTIONS

1. What is creating the under pressure in the cylinder?
2. What is used in an Otto engine to ignite the fuel?
3. What does it take to ignite the fuel in a Diesel engine?

Here comes a small repetition in the four-stroke engine, the Otto engine as well as the Diesel engine, all to make it easier to understand Hydrogen as the fuel in an engine with these principles as a basis. In a four-stroke engine, the entire working process takes place in four strokes, one stroke is the piston moving from one dead center to another, for example from top dead center to bottom dead center or vice versa. The term dead center means that when the piston reaches its bottom position in the cylinder, or top, it slows down so much that it is usually called standing still before it reverses direction and goes in the other direction, it reaches its dead center and in the different strokes, different things happen. Top dead center is sometimes abbreviated as TDC and bottom dead center as BDC. In one working cycle, the crankshaft rotates two revolutions, the camshaft rotates one. At least one inlet valve and one outlet valve are required for each cylinder. A spark plug is required to ignite the fuel-air mixture.

4.1 THE OTTO ENGINE



The four strokes in an Otto engine (Image 16)

4.1.1 STROKE 1. THE INTAKE STROKE

In this stroke the piston moves down into the cylinder. The inlet valve is open and air is sucked in by the negative pressure that occurs in the cylinder. In the inlet, can also be called intake stroke, duct is an injection valve which injects petrol at a specific time and mixes with the air. The outlet valve is closed. If the engine is so-called direct injection, only air is sucked in and the fuel is injected directly into the combustion chamber at the time that is considered optimal. If the engine is so-called supercharged using an exhaust compressor, turbo, or mechanical compressor driven by some kind of belt or chain, the mixture is pressed in using the overpressure created by it.

4.1.2 STROKE 2. THE COMPRESSION STROKE

The piston is now at the bottom dead center and facing upwards. The inlet valve closes, the outlet valve remains closed, at this rate the fuel-air mixture is compressed. When the fuel-air mixture is compressed, the effect on the engine is increased and the combustion becomes more efficient. Just before the piston reaches its top dead position, the fuel-air mixture is ignited by a spark from the spark plug.

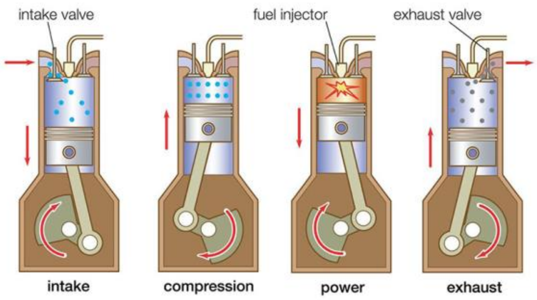
4.1.3 STROKE 3. THE POWER STROKE

At this rate, the fuel-air mixture has just been ignited and it expands at high speed, causing the piston to be pushed down with a very large force. The inlet valve is closed, the outlet valve is also closed. This stroke is the only one that creates power of all the four strokes.

4.1.4 STROKE 4. THE EXHAUST STROKE

In this stroke, the piston moves up into the cylinder. The outlet valve is open, this allows the exhaust gasses, which used to be fuel and air, to be pushed out at it and further out through the exhaust port and further out through the exhaust pipe.

4.2 THE DIESEL ENGINE'S FOUR-STROKE PRINCIPLE



The four strokes in an Diesel engine (Image 17)

You can say that the function of an Otto engine and a Diesel engine are very similar. Four strokes are required just like in the Otto engine. At least one inlet valve and one outlet valve are also required for each cylinder. The crankshaft rotates two revolutions to complete a work cycle, and the camshaft one revolution. but because the fuel is different from petrol, a spark plug is not required. The diesel is ignited by the high heat in the cylinder. The high heat is achieved by the fact that a Diesel engine has significantly higher compression than an Otto engine. The compression is approximately 20-30 bar.

4.3 THE DIESEL ENGINE

4.3.1 STROKE 1. THE INTAKE STROKE

The piston moves down the cylinder, the inlet valve is open and the outlet valve is closed. The negative pressure created in the cylinder helps draw in air. If the engine is supercharged with an exhaust compressor, turbo, or mechanical compressor driven by a belt or similar, then they force the air into the cylinder.

4.3.2 STROKE 2. THE COMPRESSION- STROKE

The piston now moves upwards in the cylinder. The inlet valve is closed and the outlet valve remains closed even during this stroke. The air is now compressed, then the air also becomes warm from the high pressure. Just at the end of the compression stroke, the diesel is injected into the hot air and ignited by the high temperature. A Diesel engine always has the injection of diesel directly into the combustion chamber, never into the intake manifold as on most gasoline engines. During cold starts, the air must be heated, a so-called glow plug sits inside the combustion chamber, which then heats the air to the temperature required for the diesel to ignite.

4.3.3 STROKE 3. THE POWER STROKE

The ignited diesel now rapidly expands and pushes the piston down into the cylinder. The inlet valve is closed, the outlet valve is also closed. This is the stroke that provides power to the powertrain. The diesel and the air have now become exhaust gasses.

4.3.4 STROKE 4 THE EXHAUST STROKE

The piston moves upwards in the cylinder. The inlet valve is closed. The outlet valve has been opened. The piston now pushes the exhaust gasses out through the open outlet valve further through the exhaust port and into the exhaust pipe.

5 HOW DOES HYDROGEN WORK IN AN INTERNAL COMBUSTION ENGINE?

In the following chapter you will learn how relatively easy an Otto or Diesel engine can be converted, step by step, to run on hydrogen fuel. This chapter also explains how to inject and ignite the hydrogen fuel in a converted engine in different ways and potential risks when misfiring.

KEY WORDS:

Ignition, ignition timing, fuel injection, conversion.

STUDY QUESTIONS:

1. Which burns at the fastest ratio hydrogen or gasoline?
2. How can the self-ignition be a risk for the engine?
3. Why is platinum coated spark plugs not a good choice for hydrogen engine?

Can you only run a combustion engine, petrol or diesel, on hydrogen? -yes, but not without making certain changes. As we have previously covered, the combustion speed is much faster on hydrogen than on petrol and diesel. It can be useful if you just know how to handle this speed. When you run an engine on petrol, you have to have an earlier ignition at high revs so that all the fuel has time to burn before the next stroke starts, otherwise you risk losing power, getting worse exhaust gas values and higher engine temperatures. With hydrogen in the tanks, it's almost the opposite, you cannot use a traditional ignition system from a gasoline combustion engine. Due to hydrogen's flammability, there is a risk of ignition occurring too early, which in that case can lead to spikes, which can also lead to worse exhaust gas values. An engine that continues to be used in this way risks major engine damage as a result, major damage to pistons and valves, in the worst-case engine crash. This problem can be solved by instead having a later ignition, just before the piston has reached its top dead position, or close to zero. This works well on the hydrogen fuel because the burning rate is so high. At low revs, on the other hand, it is an advantage if you have a slightly higher ignition. In simplified terms, you could say that you need an ignition system that works exactly the opposite of an ignition system that you have today in a gasoline engine.

5.1 CONVERTING AN INTERNAL COMBUSTION ENGINE TO RUN ON HYDROGEN

Converting an internal combustion engine to run only on hydrogen instead of running on petrol/diesel is actually possible in principle. We will explain two ways here, but there are more.

When you say "possible", it is in quotation marks. Always when you have to convert/rebuild/modify, it is always much more than you had initially expected. At the time of this writing, no pre-made conversion kits have yet been found on the market, perhaps there never will be either.

The next question that comes up is which engine type and model year to convert, but we will stick to completely general explanations without going too deep into the smallest detail. There are companies today that makes conversion kits for CNG, compressed natural gas, LNG, Liquefied natural gas and this gasses are very similar to hydrogen gas.[10]

5.1.1 STEP 1

The first thing to consider is the fuel system. The tank must be replaced with one that can handle the high pressure of 700 bar. Getting hold of such a tank will be a question in itself, currently these are not available at the local car accessories store, but there are companies specializing in developing and producing tanks for high pressurized hydrogen, or possibly you could get a bottle from a gas supplier.[11]

[10](Dimitriou and Tsujimura, 2017)

[11]‘(Kroyan et al. 2022)

Here is one example of a hydrogen tank produced by the company Doosan (Image 18).

5.1.2 STEP 2

The next step is to replace all the ordinary fuel lines that previously transported gasoline with relatively low pressure and fairly little risk of leakage. The hydrogen will be stored under very high pressure and also transported through lines from the tank to the engine where there is a high risk of leakage at all connections. So, in other words, all lines that are installed must be dimensioned according to the high pressure and volume.

The same applies to all connections and fittings, these must also meet the requirements that hydrogen makes to prevent leak out.[12]

Different fittings for high pressurized hydrogen (Image 19).

[12](Dimitriou and Tsujimura, 2017)

5.1.3 STEP 3

The engine will then get the fuel and as mentioned earlier we will take up two different approaches. What has to be done regardless of the various approaches is to replace the previous injection valve(s) that were previously intended for gasoline with injection valves that are intended for gas. Reports exist that the use of injection valves designed for gas has worked well.[13]

5.2 TWO DIFFERENT WAYS TO FEED THE ENGINE WITH HYDROGEN

One of the ways to supply the engine with hydrogen is via injection valves mounted in the intake manifold on the outside of the intake valve and thus allow the hydrogen to start mixing with the air/oxygen already outside the combustion chamber, and then with the help of the engine's negative pressure, it is sucked into the cylinder when the intake valve opens. This model has a certain risk of self-ignition because the fuel enters as soon as the inlet valve opens and there may then be a risk of the hydrogen coming into contact with parts that have such a high temperature that it ignites. It could be the spark plug that has too low a heat number and still glows, it could be residual carbon and soot deposits from the engine previously running on fossil fuel before the conversion. Or oil residues that are forced up between the cylinder wall and the piston rings due to somewhat substandard crankcase ventilation, which can glow in the cylinder. Detonation of the fuel/air mixture can also occur due to cam timing with too high an overlap and the fuel then comes into contact with the exhaust port.

The other way in which hydrogen can be supplied to the engine is to use a so-called direct injection model of engine. This means that the injection valve must sit directly in the combustion chamber. The advantage of this method is that you can control more precisely when you want the injection to take place.

5.2.1 STEP 4

Due to the combustion nature of the hydrogen, the ignition system also needs to be converted, depending on what you have as a starting point, you have to do it in different ways.[14]

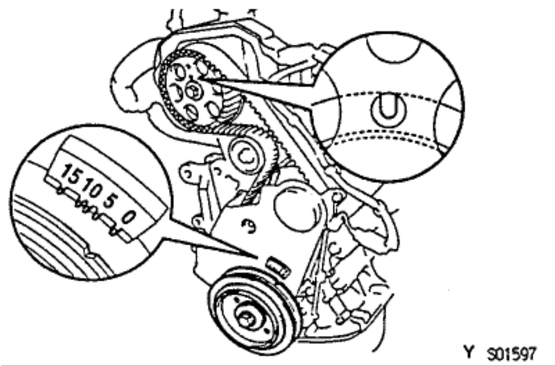
[13](Rorimpandey et al. 2023)

[14](Verhelst and Wallner, 2009)

A conventional spark plug is also used in some types of hydrogen engines (Image 20).

You can sum it up by saying that the ignition timing at high engine speeds with an internal combustion engine converted for hydrogen should be later than, for example, with traditional gasoline operation, where the ignition timing is approximately 25-35 degrees before top dead center. On the hydrogen converter, the ignition timing can be close to zero at high engine speeds, because the flame speed is so high.

On the other hand, the flame speed decreases with a leaner mixture, which for example occurs at low rpm, for example at idle, but also at low load, on the petrol engine the ignition timing is around 10 degrees before top dead center, when instead on the hydrogen converted engine it should be a little earlier ignition timing to burn the entire mixture.



The timing needs to be retarded compared to a petrol fuelled engine (Image 21).

This modification could be done by modifying the software in the vehicle's control unit according to the desired ignition timings you want to access in the different conditions the engine will be exposed to.

On an older engine with a traditional distributor that runs at the speed of the camshaft, you could instead use a distributor that is in the opposite direction to the one that should be there, which would then mean that the ignition timing is lowered at higher rpm and raised at lower rpm, such as idle.

Furthermore, spark plugs with a platinum coating should not be used because the platinum acts as a catalyst between hydrogen and oxygen and the risk of self-ignition can then occur.

When planning to convert a regular internal combustion engine that previously ran on fossil fuel containing carbon, it is extremely important to dismantle all parts in and on the engine that may contain soot particles. The cylinder head must be disassembled to access the soot that usually occurs in the combustion chamber. The valves should also be taken out so that they too can be cleaned of soot, also inside the ports, especially on the exhaust side, all soot particles should be removed. Up on the piston tops, there are usually soot deposits that must be removed.

All this work is important to do in order to counteract self-ignition that will occur if there are residual soot particles that glow. From the hydrogen, there will not be any soot deposits later because it does not contain any carbon in it or oxygen.

6 THE RESEARCH STAGE

Today, researchers around the world are in full swing developing and refining the technology for engines that can run/run better on hydrogen. They work on supplying the hydrogen to the engine in different ways, this will be explained in closer detail in the following chapter.

KEY WORDS:

Ignition, injection, different injection systems.

STUDY QUESTIONS:

1. *What system is considered the simplest way to feed the engine with hydrogen?*
2. *Which one of the exhaust gasses has shown to be challenging to reduce to reasonable figures?*
3. *Explain why the pilot injection is used in a hydrogen engine.*

6.1.1 HYDROGEN PORT FUEL INJECTION, PFI

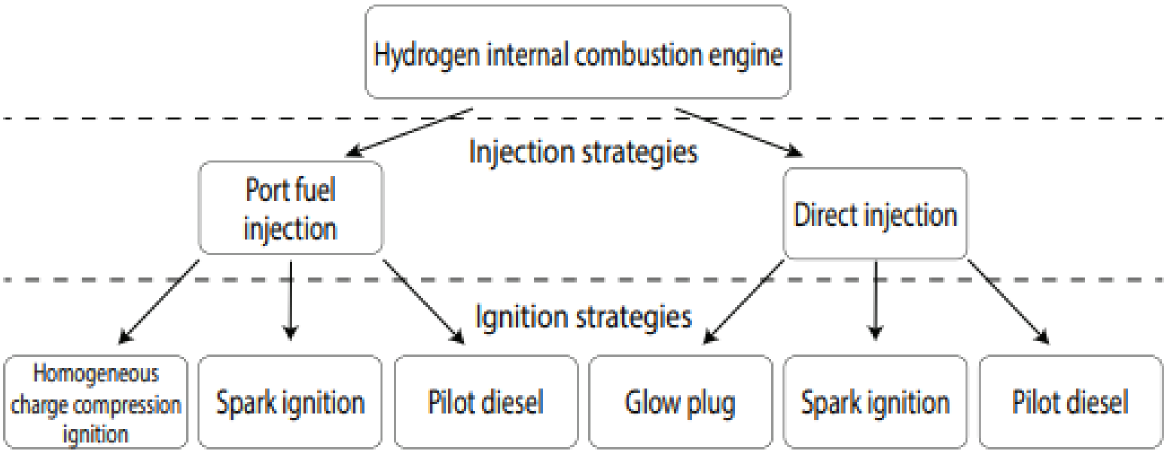
Injection into the inlet port in the intake manifold. Which means that the fuel is injected outside the inlet valve, i.e. not directly into the combustion chamber. Only when the intake valve opens and the piston moves down the fuel is sucked into the cylinder due to the negative pressure that is then created, the intake stroke. This type of injection is the most common on Otto engines. Converting this system to hydrogen operation is relatively "simple", as we previously covered. The injectors need to be replaced to be able to handle hydrogen instead of petrol, and the ignition system needs to be modified, also mentioned earlier. But there are risks with this system that we also mentioned earlier, namely premature self-ignition because the fuel enters so early. Another problem with this type of injection system is that when the fuel is injected into the intake port it pushes out the air and the engine's power is then limited. A simple description of different types of how the combustion can take place, as well as slightly different types of ignition of the fuel, follows below.[15]

6.1.2 HOMOGENEOUS CHARGE COMPRESSION IGNITION, HCCI

Homogeneously charged compressed ignition one could translate it. Without going too deep into a description of this, it is based on the injection of hydrogen taking place as we described in the PFI system, i.e. in the inlet port right next to the inlet valve but on the outside of the combustion chamber. They use a homogeneous mixture of air and hydrogen, which is also very lean. This mixture is injected directly into the combustion chamber and due to its flammability, it is ignited by the high compression and then ignites the supplied hydrogen. What has proven to be a great advantage of this system is that NOx has been reduced to really low figures as a residual product in the exhaust gasses. This, moreover, with maintained power from the engine. NOx is close to zero. But even this system needs

[15](Yip et al., 2019, s. 7)

further development to function, among other things very high compression is required to name a few.[16]



The different ways of injection for internal combustion engine (Image 22)

6.1.3 SPARK-IGNITED PORT FUEL INJECTION

This system, which is described in English as PFI SI, SI stands for Spark Ignition, i.e. an ignition of the fuel with the spark from a spark plug. PFI with SI is the most researched system when it comes to internal combustion engines that will burn Hydrogen. This system, if you have a fuel/air mixture that is extremely lean, will be able to get down to very low NOx figures in the exhaust gasses, below 100 ppm without any external treatment.

It is also desirable to reduce the amount of unwanted residual products in connection with combustion. This can be achieved through Stoichiometric relationships.

Stoichiometric relationships could be described in a simplified way as meaning that the precise correct amount of matter together with another matter of precise correct amount is included in a combustion where everything ignites. This also, eliminates any undesired residue. The use of an EGR-system reduces the NOx even further. EGR stands for Exhaust Gas Recirculation. Which means that a small amount of exhaust gasses is recirculated back in to the combustion process in order to decrease the

[16] Ibid. s. 7

combustion temperature and thereby reducing the NOx figures which are formed at high temperatures.[17]

A three-way catalytic converter is also used, which further lowers the value of NOx to values as low as close to zero. Instead of EGR, water injection into the intake manifold is sometimes used instead because it has the same effect as EGR, since in the hydrogen combustion there is only water vapor as a residual product. This system has, as we have previously experienced, some problems such as unwanted premature ignition of the mixture but also backfires that leads to engine power losses.

6.1.4 PILOT FUEL IGNITION WITH PORT HYDROGEN INJECTION

This system is based on having direct injection DI and PFI. The direct injection is for giving a so-called "pilot injection", this means that you inject a small amount of diesel directly into the combustion chamber. The diesel is ignited by the heat of compression and when hydrogen is later injected into this it is ignited. But even this system comes with certain disadvantages such as unwanted self-ignition. The NOx content is also too high for this method to be classified as zero emission, but further studies are being carried out in the laboratories. But despite the fact that PFI systems are relatively easy to convert to hydrogen operation, perhaps they should be seen more as a transition from our usual fossil-burning engines to more advanced engines that are hopefully not too far off in the future.[18]

6.1.5 HYDROGEN COMBUSTION WITH DIRECT INJECTION

Adding the hydrogen directly into the cylinder during the compression stroke itself seems to be the most promising concept as far as we have come today with the development of the engine types we have. By doing it this way, you can more or less prevent unwanted self-ignitions or back-ignitions that occur in the PFI engine system. Because the fuel injection time can be regulated as desired. You could wait to inject it so late that both valves are closed, which minimizes the exposure of hot parts.

The problem you have with hydrogen is that it takes up a lot of space when it is injected via the intake manifold and then also takes the place of the air supply. This in turn contributes to power loss that you also get rid of. This is because only the air has already been sucked into the cylinder via the inlet

[17] Ibid. s. 8

[18] Ibid. s. 8

valve, and the fuel is then supplied into the cylinder when the inlet valve is closed. However, when injecting the fuel in the compression stroke, you have to have a higher injection pressure from the injector due to the higher pressure that prevails inside a cylinder than what is required from an injector for the PFI system. In a PFI system, there is no excess pressure at all, but instead it is mostly a negative pressure instead. It has been shown that this system, which works with such high pressures, can almost be compared to the high efficiency of diesel. The system is often abbreviated with HPDI, which stands for High Pressure Direct Ignition. There are many advantages to this system, it can be made more flexible in many different situations, it can be fine-tuned in a completely different way than a PFI system. You can adjust the injection pressure, you can adjust the injection timing, you can also adjust the injection design, all this to be able to optimize the engine power to the optimum. There are a few different ways of igniting the fuel, and you can read about that further on.[19]

6.1.6 GLOW PLUG IGNITION

Glow plugs are normally used for diesel engines when starting from cold. They then glow for a short while just before the starting moment to heat up the combustion chamber and then go out when the engine is running. But when you use them to work in a direct injection internal combustion engine for hydrogen fuel, it's different. Here, the glow plug must be on all the time and a temperature of roughly 900-1100 degrees Celsius is required. But even this method shows both pros and cons, if you compare it to the Diesel engine, for example, the hydrogen engine takes more fuel, but an advantage seen in the studies was that it emitted significantly less NOx than the Diesel engine. Another problem with this type is that today you don't have any glow plugs that are able to stay on and glow all the time, but maybe this problem can be solved in the future.[20]

6.1.7 SPARK IGNITION WITH SPARK PLUG

Probably the most researched model and also the most well documented, direct injection with spark plug ignition.

In many ways, it is very similar to the model described in the previous paragraph, ignition with glow plugs. What has largely been done is that the glow plug/one has been replaced with a spark plug.

[19] Ibid. s. 9

[20] Ibid. s. 9

There may be more spark plugs than one. Studies carried out on a single cylinder engine converted for direct injection and igniting the hydrogen from a spark from a spark plug show a thermal efficiency of 40% at low to medium engine loads, which is only slightly less when compared to an equivalent Diesel engine.

What has also been noted with this model is that injection timing affects mixture homogeneity, which significantly affects engine power and emissions more than ignition timing. Delaying the injection timing from 120 degrees before TDC to 65 degrees before TDC further increases engine power. Unfortunately, this results in increased emissions of NOx, they have then tried injecting more air to lower the content, it has worked but then the effect has been reduced as a result. What has also been shown to have a major impact on engine performance is the angle at which the injector injects the fuel into the combustion chamber.[21]

6.1.8 DUAL-FUEL HIGH PRESSURE DIRECT INJECTION COMPRESSION-IGNITION ENGINE

As we mentioned earlier, igniting the Hydrogen with only compression heat is not easy. Here we will describe in a relatively simplified way how they have thought with this technology.

By using a so-called pre-injection, it has also been taken up in the models presented earlier. It can also be called pilot injection. For example, it can happen in this way: In the combustion chamber there is an injector that injects a small amount of a substance that ignites with the help of compression heat, for example diesel, it ignites and shortly afterwards the hydrogen is injected and ignited by the now burning diesel in the combustion chamber. However, in this theory there has been no information to explain how it works in reality with hydrogen. On the other hand, studies have been done with CNG, Compressed Natural Gas, which has a flammability similar to hydrogen.

Two injectors have been used, one for the diesel and one for the gas. Different angles of the injectors have had different effects. Even different pressures have had different meanings. Even in this model, they have tried injecting the gas at different times during the compression stroke and got different results from this. It has also been tried with combined injectors where the injector is designed so that both fuels are in one and the same injector.[22]

[21] Ibid. s. 10 f.

[22](Dimitriou and Tsujimura, 2017)

Here is one example described, this dual injector is developed by the company West port. (Image 23)

A setback that has emerged is that the pilot injection of diesel to start the combustion of the gas eventually builds up a layer of soot even though the amount of diesel is very small, but this problem will probably be reduced when the CNG is replaced by hydrogen, since CNG contains carbon.

6.2 PROS AND CONS WITH THE DIFFERENT METHODS

With the different methods of fuel injection or how the combustion takes place, you can say that there are pros and cons with all of them. The injectors for example have been noted that due to the hydrogen not having a lubricating effect like diesel or petrol, they have shown wear and tear which will probably be a problem in the long run. Possibly this could be solved with the help of some form of lubrication, or perhaps treating the parts that touch the item with a surface that ensures the friction between them.[23]

[23](Gültekin and Ciniviz, 2022)

6.2.1 INJECTOR ROLE

The injector has been shown to have a large role in the engine performance. The characteristics of the injector in terms of how much pressure it can handle and the size of the nozzle are directly linked to how good the injection is and how it mixes but also how the injection quantity is controlled. Thus, the design of the injectors affects how large the heat loss is at the cylinder walls and the efficiency with it, thus also the fuel consumption.[24]

What has also come to light is that the hydrogen gas has an embrittlement effect on certain metal alloys, which can become a problem during long-term use.

Further obstacles that must be overcome are for example, how to handle hydrogen's high diffusivity capability which allows it to pass through several types of different material.

The injectors, for example, may be exposed to the hydrogen, which can then lead to the function being impaired or perhaps completely absent.

A prerequisite for the development of hydrogen as a fuel in internal combustion engines is that one focuses on the problems one has, for example, with different materials that can cope with hydrogen's different properties. The high pressures used in some of the systems previously presented. The design of the gas lines and that you can seal in a safe way in all the connections between different components. How fuel tanks are designed and a construction on them that ensures absolute tightness. That the injectors are designed specifically for hydrogen gas, today we use a lot of injectors that are actually intended for other types of gasses, CNG, LPG or BIO- gas. But development is constantly moving forward and what is written today may be history tomorrow.

6.3 THREE DIFFERENT INJECTION TYPES

6.3.1 ELECTRO-HYDRAULIC-ACTIVATED (NTSEL)

This type of injector requires hydraulic fluid (usually diesel) under high pressure.

The injection pressure is limited to 200 bar. During the actual injection the solenoid is activated which then releases the pressure in the diesel which is in the upper part of the injector, the hydrogen which is under high pressure can then lift the injection needle from its seat and the injection takes place. In

[24](Verhelst and Wallner, 2009)

this type of injector, there must be such a high pressure on the diesel that the needle seals against its seat in the closed position. The diesel also ensures that certain moving parts in the injector are lubricated.[25]

6.3.2 SOLENOID-ACTIVATED (WESTPORT)

The company Westport has developed this injector, it is their first generation and it is completely solenoid driven for the purpose of DI and Hydrogen fuel. It is limited to 150 bar. Some malfunctions have been reported on it, including some movement restrictions on the needle.

Hoerbiger Valve TEC GmbH has also developed a similar solenoid driven also developed for DI and Hydrogen fuel with a maximum injection pressure of 100 bar.[26]

6.3.3 PIEZO ACTUATED (WESTPORT)

This is of the second generation and can withstand pressures up to 250 bar. Here the needle is activated by a piezo element, from an analogue voltage that regulates the movement of the needle and enables a very fast response. It has a short opening time of 0.5 ms. Furthermore, the service life is improved due to the flexible control of the needle speed, which allows the speed of closing to be reduced, thus reducing the closing pressure.[27]

7 CONCLUSIONS

This chapter shines light on the advantages of the conversion of existing engines and vehicle and vessel transport and production of the future. It also takes a more sentimental point of view on the future of vintage vehicles. In a world where scientists constantly find new solutions and a world where humanity are given new challenges with the environment, these are perspectives we must have in mind.

[25] (Yip et al., 2019, s. 18)

[26] Ibid. s. 17

[27] Ibid. s. 17

KEYWORDS:

shifting engine production, conversion advantages, saving vintage vehicles, the future of vehicle and vessel transport.

STUDY QUESTIONS

1. *What challenges of the future can hydrogen help to solve?*
2. *What are the advantages of using hydrogen in an internal combustion engine vs. in a fuel cell?*
3. *What possible advantages and disadvantages of shifting to a hydrogen-based future do you see regarding both the individual and society?*

7.1 THE ADVANTAGES OF CONVERTING EXISTING ENGINES

An advantage that has been found in running internal combustion engines with Hydrogen, instead of in fuel cells, is that the hydrogen does not have to be quite as pure to work in an internal combustion engine as in one with fuel cells. Another advantage you see when using internal combustion engines is the possibility to switch between different types of fuel. Furthermore, using already proven technology will keep costs down at the factories.

Whether or not there will be conversion kits available in the future is a question that no one can answer at the moment, but it would be more environmentally friendly to switch over from fossil fuels to fossil-free fuel as soon as possible.

7.2 WHY HYDROGEN IN AN INTERNAL COMBUSTION ENGINE

In conclusion; Perhaps that is a legitimate question; why are we trying to develop the Otto engine or Diesel engine to run on hydrogen when it seems that they are already on their way out of society?

There is no quick and easy answer to that. It is absolutely the case that the vehicle that uses fuel cell technology has a higher efficiency than an Otto engine or Diesel engine that has been modified to run on hydrogen.

One way of looking at this is that we already have a large number of Otto engines and Diesel engines around the world. Still these engines largely dominate the market compared to electric vehicles.

Being able to replace these in a short time will be an impossibility, and at the same time it is of the utmost importance to take action very soon, because the global environment is threatened.

For factories to shift production from combustion engines to electric engines Changing all factories today that produce combustion engines for our vehicles to instead produce electric engines will be a big challenge because it has to happen rapidly. The same applies to battery production and the substances required for them. What we know today is that those are only found in limited quantities in a few places in the world.

In some parts of the world, it is not financially feasible, and will not be in the long term, to replace one's vehicle with an electric or fuel cell-powered one. Here the solution of rebuilding existing vehicles could be a good alternative.

The same applies to shipping, heavy traffic and airplanes, here the option of rebuilding existing engines for hydrogen operation could spare companies from large financial losses due to scrapping out a well-functioning fleet.

Yet another area today completely dependent on fossil fuel is the area of enthusiast vehicles, on the ground, in the water or in the air. Within this area it would also be welcome with an option to be able to continue using these vehicles. The same also applies to all types of motor-related racing.

Yet another aspect is more of an emotional or nostalgic one. Some people find it difficult to scrap their old combustion engines and find a certain charm in hearing the sound of them.

It could be that one should regard the development of hydrogen fuel for the Otto and diesel engines as a transition until those vehicles have reached the point where they need to be replaced.

This replacement of new vehicles should at least be considered when we talk about commercial and private use cars.

On the other hand, where there are no financial possibilities, hydrogen fuel could be a good alternative to be able to continue using vehicles that today burn fossil fuels, petrol or diesel.

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Image 23: Private image of dual fuel injector from West port.

10 ABBREVATIONS

BDC	Bottom Dead Center
BIO	Biological
CNG	Compressed Natural Gas
DI	Direct Injection
EGR	Exhaust Gas Recirculation
HCCI	Homogeneous Charge Compression Ignition
HPDI	High Pressure Direct Ignition
H_2	Hydrogen
ICE	Internal Combustion Engine
LNG	Liquified Natural Gas