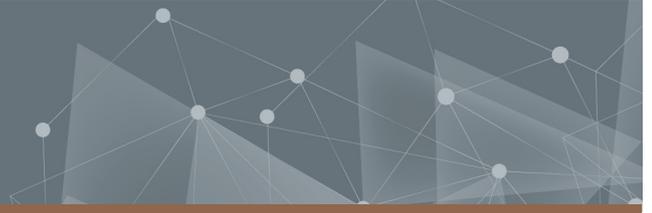




CHALMERS
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A Literature Review of Hydrogen Internal Combustion Engines

An evaluation of recent developments and challenges surrounding the use of hydrogen as fuel in internal combustion engines.

Master's thesis in Mobility Engineering

Hjalmar Lindqvist
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Department of Mechanical and Maritime Sciences

CHALMERS UNIVERSITY OF TECHNOLOGY
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MASTER'S THESIS 2024

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Abstract

This thesis reviews the current challenges of the hydrogen internal combustion engine through a literature study conducted for two main reasons. Firstly to provide an overview of the operation of a hydrogen internal combustion engine and secondly, to gather test data from previous research as well as the researchers' conclusions. From the literature review, it was presented that hydrogen as a combustion fuel still poses challenges surrounding combustion stability, power density and NO_X emissions. Abnormal combustion such as pre-ignition and knock occur often at air-to fuel ratios close to the stoichiometric ratio (34.2:1) causing operation around $\phi = 0.5 - 0.6$ to be more optimal. With knock-suppressing methods such as water injection or exhaust gas recirculation, a lean air-to fuel mixture is required to extract maximum possible power while maintaining stable combustion at all engine loads.

In the results the test data from all studies were compared and evaluated. Researchers do not seem to agree on whether port fuel or direct injection is most desirable. Using the different injection systems will therefore come with differing issues to solve. While similar thermal efficiencies to gasoline engines have been achieved in the past 15 years power is still lacking. The highest BMEP achieved by a study (1.215MPa) is around half that of a conventional turbocharged gasoline engine in a passenger vehicle. The studies focusing on performance have been conducted at low engine speeds with low displacement engines providing little data above 2200 RPM showing concern whether a hydrogen combustion engine will have the same characteristics when upscaled and needing more air. Researchers focused on engine performance also lack data regarding NO_X occurrence at different operating points but benefit from the consensus between studies to utilize lean air-to-fuel ratios. However, as of today, producing one ton of hydrogen emits five times the amount of CO_2 meaning that until hydrogen production can be done with zero emissions the engine concept can not be considered emission-free.

Whilst the research has proven that it is possible to construct and operate a hydrogen internal combustion engine there are still areas which need to be improved upon for the engine to function smoothly in a vehicle. Tests need to be done on larger scale engines where factors such as air supply and engine speed can be tested on the road.

Keywords: Internal combustion engine, hydrogen combustion, zero emissions, knock, pre-ignition.

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Hjalmar Lindqvist, Gothenburg, 05 2024

Petter Overby, Gothenburg, 05 2024

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

A/F	Air-To Fuel ratio
BMEP	Brake Mean Effective Pressure
BTE	Brake Thermal Efficiency
BTDC	Before Top Dead Center
BTDCf	Before Top Dead Center firing
CAD	Crank Angle Degree
CI	Compression Ignited
COV	Coefficient Of Variance
CR	Compression Ratio
DI	Direct Injection
EGR	Exhaust Gas Recirculation
EOI	End Of Injection
ER	Equivalence Ratio
FVA	Flammability by Volume of Air
H_2ICE	Hydrogen Internal Combustion Engine
ICE	Internal Combustion Engine
IMEP	Indicated Mean Effective Pressure
KI	Knock Intensity
MON	Motored Octane Number
PFI	Port Fuel Injection
RON	Researched Octane Number
SI	Spark Ignited
SOI	Start Of Injection
TDC	Top Dead Center
VE	Volumetric Efficiency
VED	Volumetric Energy Density
WI	Water Injection

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1

Introduction

1.1 Hydrogen as a fuel

The ingenuity of the hydrogen combustion engine in the past years has been somewhat overshadowed by the rising popularity of the battery electric vehicle. However, considering issues with range, charging time and energy demand the future has substantial hurdles to overcome should the entire world shift to battery-electric vehicles. The hydrogen internal combustion engine (H_2ICE) instead shows promise to replace fossil fuel in an Internal Combustion Engine (ICE) with virtually zero exhaust greenhouse emissions. With the ever decreasing supply of fossil fuel reserves an alternative becomes more imperative every year as the price of fuel also continues to rise. The hydrogen combustion engine has existed for over 200 years with Francois Isaac de Rivaz designing the De Rivaz engine in 1806 [1]. However, to this day, a design of the engine has not been completed which is effective and reliable enough to compete with the fossil fuel combustion engine.

The two main ways of utilizing hydrogen as a power source are through combustion similar to fossil fuels or power cells. A power cell makes use of the oxidization of hydrogen to generate electricity with water as its only by-product [5]. As a combustion source, hydrogen can be used instead of fossil fuel in a combustion engine. However, it does suffer from complications regarding its flammability which could result in undesirable combustion. [2] Storage of hydrogen in a vehicle can also be an issue as it has to be kept pressurised and cold to maintain liquid form resulting in heavier components and larger energy losses.

Hydrogen (H_2) is a flammable gas which makes it very attractive as an energy source [2]. With adjustments, it can be used as a substitute for fossil fuels in combustion engines and gas turbines. Hydrogen can also be produced in different ways through methods like water splitting, or thermochemically from biomass [3]. Whilst the production of hydrogen requires energy, which in today's society comes from both greenhouse emitting methods and renewable sources like solar and wind power, it could potentially be produced with zero emissions should the future continue its shift to renewable energy sources [4]. Hydrogen is then also storable, making refueling quicker compared to battery electric vehicles which need an electric grid to recharge. Whilst other potential renewable fuels such as biodiesel or vegetable oil also exist, hydrogen is one of the few fuels which does not contain carbon which makes a huge difference in emissions.

1.2 The Internal Combustion Engine

The spark-ignited (SI) together with the compression ignited (CI) ICE are still used in a majority of vehicles sold as of 2022. Battery electric vehicles globally only made up around 14% of sales that year which is an increase from 9% in 2021 and 5% in 2020 [6]. The usage of fossil fuel-based ICEs results in that global transportation currently accounts for more than one third of global carbon emissions annually [7].

Modern-day ICEs normally operate with four separate strokes, namely intake, compression, combustion/power and exhaust stroke [8]. Depending on whether the injection type is port fuel injection (PFI) or direct injection (DI), vaporized fuel will either be supplied to the combustion chamber together with the air via the intake port or directly into the chamber. When the piston then starts going up again, the air-fuel mixture is compressed to the correct compression ratio (CR). After this, the mixture will combust either from the high compression or by a spark and the piston will be pushed down for its power stroke. The piston then goes up again pushing out all exhaust gasses, whereupon the complete cycle starts over [9].

1.3 Scope and Limitations

The purpose of this project was to review the status and complications of hydrogen as a replacement for fossil fuels in the combustion engine. The work was limited to, and focused on, the characteristics and emissions of hydrogen in the internal combustion engine. Therefore, there were parameters such as hydrogen power cells or storage within the vehicle not taken into account. The aim was to produce a review which takes all parameters of the engine and the remaining challenges to overcome into evaluation.

2

Literature Study

2.1 The Hydrogen Internal Combustion Engine

H₂ICEs are very similar in design and function to regular gasoline and diesel ICEs. What elevates the H₂ICE compared to traditional ICEs is the emissions from this kind of engine as a H₂ICE theoretically will only produce water and nitrogen oxides (NO_x) as emissions. With the atmosphere containing mainly nitrogen and oxygen the reactions in equations 2.1-2.3 occur [10]. However, in practice, this is not the case since factors such as carbon-based lubricants can be mixed into the combustion. Moreover, improper timing of hydrogen injection can also cause hydrogen slip. As the exhaust valve is still fully or partially open when fresh hydrogen is injected this results in unburnt hydrogen being present in the emissions (see further in section 2.2).



Like with regular gasoline ICEs, the risk of hydrogen passing by the pistons and entering the crankcase of the engine is present. The hydrogen then has a risk of autoigniting due to the high heat potentially resulting in an engine fire [11]. H₂ICEs have also been shown to suffer compared to traditional gasoline engines at several factors such as power density and in-cylinder autoignition [1]. Unpredicted autoignition can occur within the cylinder in the form of pre-ignition or knock which is documented in depth in section 2.3.

2.1.1 Injection strategies and timing in the H₂ICE

How fuel is injected into the engine and the result of which can be divided into two different viewpoints which are the injection method and its resulting parameters as well as the injection timing. The differing injection methods are divided into two strategies, namely port injection and direct injection (see figure 2.1) [9].

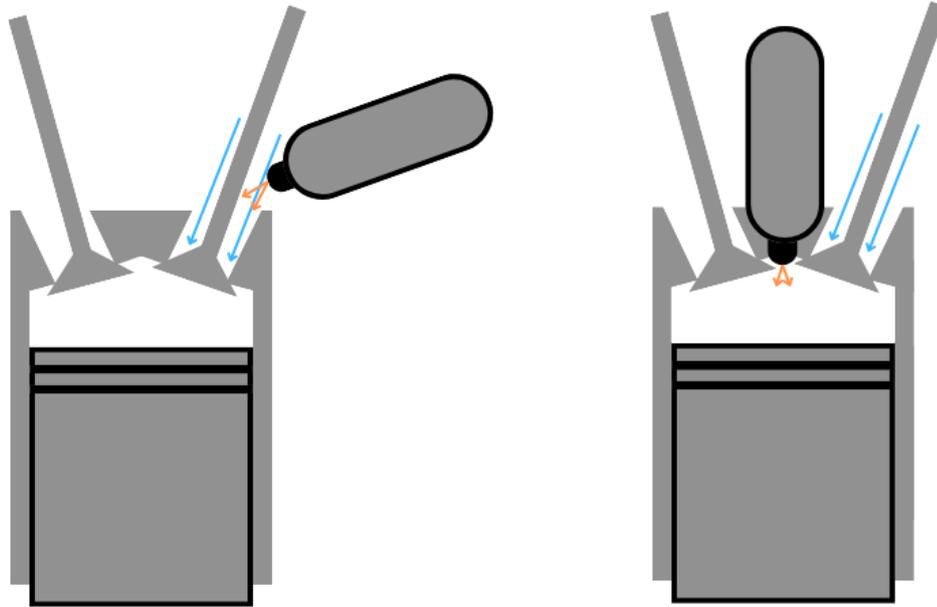


Figure 2.1: How fuel (H_2) is added: left, port fuel injection, right, direct injection (air and fuel flow marked in blue and orange respectively).

- **Port Fuel Injection:** In a PFI the fuel is injected before the combustion chamber together with the incoming air. However, PI does it by spraying the fuel directly into the air stream in the intake manifold before the valve and combustion chamber [12].

One of the issues with PFI is highlighted in a study by Xie Cheng *et al* [13] on injection timing-based backfire control. Regarding injection timing, the injection must be timed very well with the opening and closing of the intake valve as an early injection, 473 crank angle degrees (CAD) before top dead centre (BTDC) for 3000rpm caused the hydrogen to pool around the unopened intake valve. When the valve opens warm residual gasses in the cylinder could ignite the hydrogen causing backfire into the intake manifold. Similarly, late injection (90 to 53 CAD BTDC for 3000rpm) would be injecting hydrogen as the intake valve was closing meaning the mix could again possibly pool around the intake or not enough fuel would enter the cylinder. The optimal start of injection (SOI) from this study proved to be 403 CAD BTDC since at this point the valve would be open enough to allow all hydrogen to enter the cylinder. With increasing engine load, SOI was advanced to optimize the injection strategy.

Regarding the performance of PFI, the injection in a separate chamber allows for creation of a homogeneous air-fuel mixture [14]. A homogeneous mixture

provides a stable flame and short combustion duration. However, the downside of pre-mixing is that volumetric efficiency decreases significantly. The hydrogen takes up space which otherwise would be taken up by air in the intake, thereby reducing the total amount of air which can enter the cylinder during each intake stroke. Hydrogen also has a lower volumetric energy density than gasoline meaning that a PFI hydrogen engine will always be at a deficit to an equivalent PFI gasoline engine.

- **Direct injection:** Direct injection engines sprays fuel directly into the cylinder instead of the intake manifold [12]. For hydrogen the design utilizes one or more injectors that are placed somewhere in the cylinder above the piston where the fuel jet can be sprayed [15]. Utilizing direct injection in a hydrogen engine instead of port injection has a clear advantage as two issues are mitigated [16]. Firstly, by injecting the hydrogen after the intake valve has closed no hydrogen will be able to re-enter the intake manifold thereby eliminating the risk for backfire. Secondly, the volumetric efficiency loss characteristic for port injection will also be mitigated as only air is let in through the intake valve.

Yang Li *et al* [17] studied the optimal injection timing for DI to achieve proper mixing where hydrogen needs to be injected early enough to mix with the air before combustion. With a SOI interval between 128 to 43 CAD BTDC the mixture at later injection would drop off in mixture uniformity quickly after 88 until 48 CAD BTDC. In comparison the uniformity between 128 and 88 CAD BTDC appears to be significantly higher and was not decreasing as quickly over a similar CAD window. It was concluded that the most optimal injection time for mixture uniformity for DI engines would be before 88 CAD BTDC.

Regarding injection pressure Zhen Hu, *et al* [16] states that a low pressure injection (2MPa) has the advantage of simplifying and improving the fuel delivery system [17]. In particular, the durability, lifespan and sealing of the injectors will increase with lower friction within the injector. High pressure injection's main advantage however is the better mixture penetration because of its higher energy and turbulence jet characteristics, which can cause better total mixing. This means that the injection duration can be shortened and SOI controlled in more detail possibly allowing for better operating points. So high pressure injection in general has better performance parameters, although the duration of the engine will suffer. However, to mimic this for low pressure injection, altering the injection nozzle is an option. This could change the jet penetration characteristics, potentially providing similar or better performance for low pressure injection compared to high pressure injection. Zhen Hu, *et al* [16] suggested using a low pressure nozzle diameter between 2-3mm in comparison to a regular 1mm high pressure injector, as the tests provided similar or better results utilizing low pressure rather than the high pressure without any of the issues that would come with high pressure injection.

For the performance of a DI engine compared to PFI the main advantage apart from the superior volumetric efficiency is related to better optimization of the

injection [18]. Since the injection will be directed into the cylinder, changes on the injector and nozzle geometry can greatly affect the mixing of the fuel right before combustion. This then means a better influence can be had on the stratification of the mixture with controlled rich and lean regions [19]. Thanks to this, the flame speed and propagation and thereby the combustion process can be tuned to an optimal state. The main prospect of tuning DI for stratified mixtures is the possibility of faster controlled, stable combustion improving thermal efficiency. More information on stratification can be seen in section 2.2.1 and 2.3.1.

2.1.2 Ignition timing and compression ratios for the SI and CI H₂ICE

While both spark and compression ignition can be used for hydrogen to some extent, the resulting engine performance has varied [20]. Ikegami M *et al* [21] reports that when operating a one-cylinder CI engine at a CR usually used for diesel (17.6:1), the engine had large issues with knock. Furthermore, when running the engine for multiple cycles the combustion would not always occur, only happening on average every other cycle. When combustion did occur it was often delayed, taking place at varying CAD:s. This was shown to be the case for both swirl- and pre-chamber mixing of the fuel as both methods showed the same significant issues, also causing pre-ignition and backfire. Similarly Antunes, *et al* [22] encountered high combustion instability utilizing a 0.855 litre single-cylinder CI engine reaching up to COV=25% posing a risk of damaging the engine.

As hydrogen has a high autoignition temperature (844K) the fuel requires higher CR:s than diesel in order to combust. However, as the fuel is hindered by abnormal combustion, spark ignition might be the better alternative [20]. Dennis *et al* [23] reports testing ratios between (10.3:1 and 14.5:1), where brake thermal efficiency (BTE) would stay around 38% with low NO_X emissions for lean running conditions. Similarly, Lee *et al* [24] ran an engine with a ratio of 10.5:1 where similar thermal efficiencies to conventional gasoline were achieved together with low NO_X emissions. This was done by retarding the ignition timing and utilizing a low equivalence ratio (ER) ($\phi = 0.6$) to reduce the risk of abnormal combustion.

Al-Baghdadi [25] reports on how CR:s will affect a multitude of aspects of the engine. It was shown how hydrogen pre-ignite frequency increases at higher compression ratios, maxing out at 12.5:1 with an ER of $\phi = 0.6$ and optimal timing. Furthermore, regarding power depending on CR the optimal point was around 11:1. This is further substantiated in a study by Jilakara *et al* [26] where the optimal CR was concluded to be at 12:1 or lower on a turbocharged 2.5 litre engine in order to avoid knock.

As CR increases, ignition has to be advanced closer to top dead center (TDC) [25]. In addition, as the ER approaches 1, the ignition timing also has to be closer to TDC for a specific CR compared to a higher or lower ER. The timing advance based on CR is caused by more favourable ignition conditions and a reduction in ignition lag, which is a result of the higher temperatures and pressures in the cylinder as

well as higher flame speeds caused by the high compression. Similar reasons are also the cause for the shift in timing for equivalency ratios over or under 1 as the rich or lean mixtures will cause lower flame temperatures and slower flame propagation, with less combustible oxygen for the former and lower energy release for the latter. Furthermore, as the speed of the engine increases the ignition has to occur earlier due to the decrease in burn time at high engine speeds. This is worsened further by the higher tendencies for turbulence at high engine speeds. Optimal igniting timings for these parameters are therefore given between 4 and 20 CAD BTDC for a CR between 12 and 6:1, and between 5 and 21 CAD BTDC for engine speed. In a simulation study Yun *et al* [27] analyzed the optimal ignition timing for differing loads on a single-cylinder PFI engine. It was shown that for high and medium loads a range of 10-18 CAD BTDC was optimal, while for low loads it was different with an optimal range of 18-26 CAD BTDC.

In order to mitigate undesired autoignition the ignition system needs to have a low residual charge [28]. Additionally, since high pressure hydrogen works as an insulator presenting the need for spark plugs with a smaller spark gap than regular ones are needed with the optimal distance being around 0.4mm. This partially solves the issue with residual energy as well, since a smaller spark gap will allow for lower ignition voltage and thereby less residual energy. The ignition system can otherwise be designed so that it is properly grounded or with a different resistance in the ignition cable, which also will decrease the residual energy in the system. Lastly, the spark plug electrodes should not be made from platinum to avoid hotspots caused by a catalytic reaction with the hydrogen [29].

2.1.3 Hydrogen assisted combustion

Another way of utilizing hydrogen is together with another fuel to lower emissions [30]. Tomita, *et al* [31] experimented with the hydrogen and diesel combination ranging from 0 to 80% hydrogen with hydrogen being port injected together with the supplied air. The study shows how the particulate emissions can be reduced to near zero by the use of 60% hydrogen or more whilst carbon monoxide and dioxide decrease steadily with the increase of hydrogen used. NO_x are reduced to near zero with extremely early injection timing allowing the hydrogen, air and diesel to mix properly. Injection after 50 CAD BTDC shows potentially higher NO_x emissions than the equivalent diesel engine. Similarly, in Lambe and Watson's earlier study 65 to 90% of the total fuel amount was hydrogen with diesel as the pilot ignition source [32]. Together with water injection as a knock suppressant, the engine was able to achieve performance equal to a pure diesel variant with substantially lower emissions reducing greenhouse gases and particulates by around 80%.

Another study done by Shirk, *et al* [33] focused more on hydrogen as a smaller supplement using 5 to 10% hydrogen together with diesel (B20). The investigation concentrated on the partial replacement of hydrocarbon based fuel with hydrogen showing that small benefits in emissions are possible to achieve while maintaining engine efficiency. Even though the benefits were small it shows how hydrogen can

be used to reduce the amount of hydrocarbon based fuel used and since the system uses very little hydrogen the implementation could be quite simple.

2.2 Emissions

The fossil fueled ICE produces greenhouse gases with both direct effects on human health and the global ecosystem. The type of emissions produced are summarised in table 2.1 but may vary in amount depending on engine parameters such as engine temperature and type of fuel.

Table 2.1: Types of emissions [34]

Greenhouse gas emissions	Harmful emissions
CO_2 (carbon dioxide)	THC (total hydrocarbons)
H_2O (water vapor)	NMOG (non methane organic compound)
N_2O (nitrogen dioxide)	NO_X (nitrogen oxides)
CH_4 (methane)	CO (carbon monoxide)
	Particulate matter (PM)
	HCOH (formaldehyde)

2.2.1 Combustion emissions

Shifting completely to hydrogen most of the emissions in table 2.1 are no longer a concern as the fuel does not contain any carbon. The most important emission component remaining from combustion of hydrogen is NO_X which is still present. A study in 2008 performed on the BMW Hydrogen 7 using a hydrogen port injection combustion engine resulted in NO_X emissions of 0.0008 g/km , whereas the euro 6 standards require vehicles to be below 0.08 g/km [35]. The hydrogen 7 configuration was however not deemed a zero emissions car by the U.S. Environmental Protection Agency (US EPA) as the engine still used oil as lubrication which could enter the combustion chamber emitting carbon based particulates [36].

Later research on hydrogen combustion has been divided on whether the optimal way of running the engine is with a lean air-to fuel (A/F) ratio or closer to the stoichiometric value (discussed more in section 2.3) which has varying effects on the amount of NO_X emitted. During operation with A/F ratios closer to stoichiometric or higher loads, as engine temperatures rise the occurrence of NO_X increase drastically. In figure 2.2 the increase in NO_X ppm is visualised based on data from [37]. With a quite steep increase in NO_X concentration as the A/F approaches the stoichiometric ratio, the engine load also affects how early the NO_X concentration starts to increase.

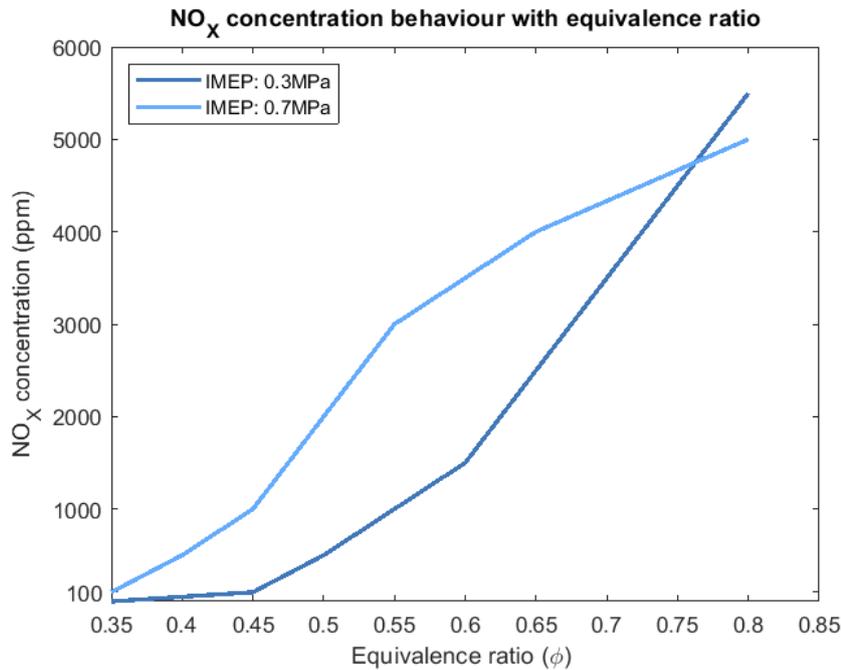


Figure 2.2: Increase in NO_x concentration with equivalence ratio ϕ (data retrieved from [37])

In these cases an exhaust aftertreatment system might not be enough and could require assistance from exhaust gas recirculation (EGR) or split injection which has been proven to lower emissions but results in higher engine complexity and in lower thermal efficiency [38]. Split injection as proven by Kalaskar, *et al* [39] halved the ppm of NO_x emitted but results in significant hydrogen slip in the exhaust meaning unburnt hydrogen is emitted. Whilst this is not a large issue regarding toxic emissions, the usage of the fuel for split injection is not ideal as it is constantly emitted from the engine which will have a negative impact on the fuel economy of the engine. Matthias *et al* [40] also studied the effect of injector nozzle geometry by comparing a 4-hole nozzle to a 5-hole nozzle injector seen in figure 2.3. As homogeneous combustion of hydrogen reaches a peak production of NO_x around $\phi = 0.8$, utilizing the 4-hole nozzle allowed for the hydrogen-air mixture to become less stratified and thus less potent for producing NO_x compared to the 5-nozzle. Further research on injector geometry will evidently have a future impact but is unfortunately scarce as other issues surrounding hydrogen combustion are still the main focus.

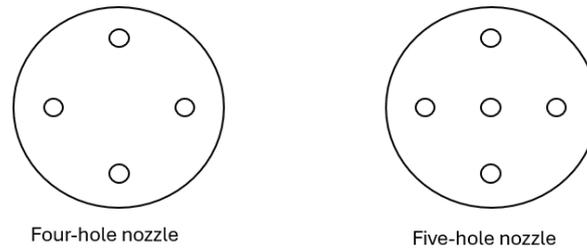


Figure 2.3: Different nozzle geometries [40]

Emissions surrounding hydrogen assisted configurations vary strongly as the ratio of hydrocarbon fuel to hydrogen effects the results. As mentioned previously in section 2.1.3 studies have varied from small to high amounts of hydrocarbon based fuels together with hydrogen. By keeping hydrogen as the main fuel with smaller amounts of diesel in a CI engine the emissions are regularly very low compared to a normal diesel engine, but since the energy source is not purely hydrogen the emissions can never become zero.

2.2.2 Hydrogen production emissions

One consideration that has to be made regarding the emissions from hydrogen fuel is the emissions created when hydrogen is produced. Looking at data provided by the National Oceanic and Atmospheric Administration it's clear that hydrogen gas is very scarce in earths atmosphere, being the eighth scarcest gas with a concentration of only 0.53 ppm whereas gasses such as oxygen and nitrogen together makes up around 99% [41]. Due to this, Pavlos Dimitriou [42] argued that hydrogen which could be used fuel would have to be extracted through other means which, in contrast, could be fossil based and therefore potentially produce harmful emissions. Dimitriou explained how 95% of modern hydrogen production is based on fossil fuels and utilizes material such as natural gas and coal. The three main methods used to produce hydrogen, namely natural gas reforming, gasification, electrolysis and where the type of fuel as well as its handling method of residuals can be divided in different categories seen in table 2.2 [43].

Table 2.2: Types of hydrogen production categories (95% of today's production is made up of gray production) [43]

	Grey Hydrogen	Blue Hydrogen	Green Hydrogen
Fuel	Natural Gas	Natural Gas	Water & green electricity
Residual product	CO_2	CO_2	O_2
Storage	Emitted into atmosphere	Underground	Emitted into atmosphere

The main issue with producing hydrogen gas is that it needs to be extracted from its bound form. Natural gas and coal are excellent for hydrogen production, but

also biomass, ethanol and even water are also good hydrogen carriers [44]. The problem then becomes finding a process to extract hydrogen gas from these sources as efficiently and sustainably as possible.

2.2.2.1 Steam Reforming and Gasification

Both steam reforming and gasification are similar methods to produce hydrogen by utilizing fossil fuels or biomass produced alcohols. With steam reforming being the most favored method natural gas is by far the most used fuel, making up 48% of the total hydrogen production [45]. The main advantage of fossil fuels is that they can be used both as an energy source for the process and also as the hydrogen extraction source. The major drawback is that for every ton of hydrogen produced through reforming of fossil fuels, between 2.5 and 5 tons of carbon is released as carbon dioxide, roughly translating to between 7.5 to 15 tons of CO_2 [46]. Furthermore, as with all other fossil fuels, natural gas exist in limited quantities and in 2013 reserves were expected to be depleted by 2073 with the usage at that point [47]. Today that number is very similar and the natural gas reserves are expected to be completely depleted by the end of 2070 with the current usage [48]. Utilizing biomass based fuels solves the problem surrounding a renewable fuel source but still emit greenhouse gases during production just like when using fossil fuels [49]. These processes which are also referred to as hydrocarbon reforming, along with hydrocarbon pyrolysis and plasma reforming, are currently responsible for a majority of the world hydrogen production, and is releasing around 830 million tons of CO_2 annually [50].

2.2.2.2 Water electrolysis

The potential of water electrolysis presents the possibility of producing hydrogen solely with green energy such as solar or wind power [51]. The process electrochemically splits water into hydrogen and oxygen, meaning that the only required resources theoretically are water and electricity. The reason why only around 4% of the total hydrogen produced is done through electrolysis is partly because its complexity but also because of the massive amounts of electricity needed. In 2022 38.6% of Europe's electricity production came from fossil fuels, meaning that using electrolysis would still not be completely emission free as long as the supplied energy is not emission free either [52]. Therefore, in order to expand the production through electrolysis, the worlds electricity production would need to advance as well.

2.3 Challenges with hydrogen combustion

While the prospect of hydrogen as an alternative fuel is very attractive in the strive for zero emission vehicles, there are still complications to be solved in regards to the engine's functionality.

2.3.1 Pre-ignition

A stoichiometric hydrogen-air mixture's required energy to combust is around one tenth of the required energy for a hydrocarbon-air mixture such as gasoline. This results in a higher tendency of pre-ignition from potential hotspots within the combustion chamber which could further develop into engine knock (discussed further in section 2.3.3). During constant operation, the hotspots occur mostly on valves or spark electrodes as a result of not being cooled enough. It can also be caused, or rather helped, by pyrolysis of lubricant residues left over in the combustion chamber after the combustion has occurred. Lubricants might enter the combustion chamber via the crankcase and be present during the combustion leaving hot carbon deposits which may act as a catalyst for the pre-ignition [9]. This type of abnormal combustion is a problem which increases as the strive for efficiency continues with the downsizing of engines and increased CR:s resulting in higher engine temperatures [53].

Kalaskar, *et al* [39] reported that a way to mitigate the risks of pre-ignition is by the use of stratified injection. Controlling the mixing process allows for an overall A/F closer to stoichiometric reducing the need for extreme forced induction. The stratified operation also allowed for an A/F closer to stoichiometric without encountering abnormal combustion at almost double the engine load compared to a homogeneous injection strategy. Further, Rajasegar, *et al* [54] recently stated that the ignition delay of hydrogen is extended as pressure is increased meaning that boosted intake pressure together with late injection timing could be beneficial to avoid pre-ignition.

2.3.2 Air-to fuel ratio

The stoichiometric A/F ratio is the amount required to achieve complete combustion. Compared to gasoline, hydrogen's stoichiometric A/F ratio (see figure 2.4) is much higher meaning a lot of air is required per amount of fuel injected [55]. The high stoichiometric ratio of hydrogen introduces two main issues, one of them being the previously mentioned minimum ignition energy in section 2.1.2, which is very low at the stoichiometric ratio increasing the risk of abnormal combustion. The other issue being the amount of air needed to be supplied to the combustion chamber exceeding that of normal forced induction methods in commercial vehicles. Additionally, hydrogen also has a very high and wide flammability by volume of air (FVA). This is the range between the percentage of fuel needed for a fuel-air mixture to combust, to the point where the mixture will be too rich to combust. Compared to gasoline which has a FVA of 0.6-7.5%, hydrogen instead ranges between 4 to 75% at 293K [56]

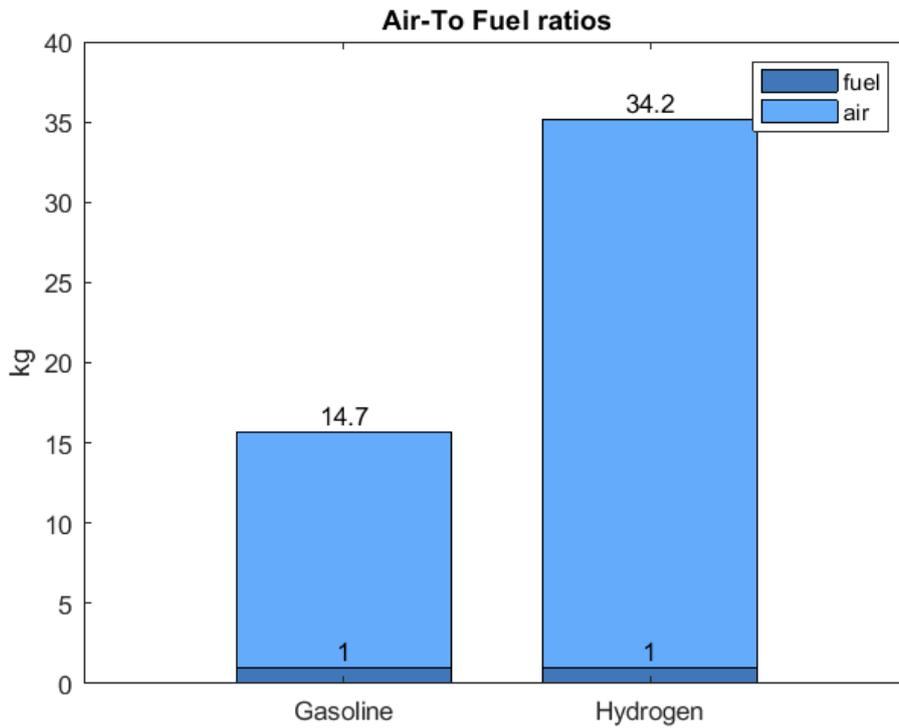


Figure 2.4: stoichiometric Air-To Fuel ratios for gasoline versus hydrogen.

At stoichiometric A/F hydrogen's minimum ignition energy is at its lowest being less than a tenth of gasoline or natural gas [57]. This means that, although being the optimal ratio for complete combustion, it is near impossible for an engine to run at these conditions because of the as before mentioned pre-ignition risk. The minimum ignition energy, however, increases for hydrogen with either a lean or rich mixture lowering the risk of unpredictable combustion events. With lean operating conditions being the most optimal of the two, a pre-ignition limit can be set for an engine ensuring safe operating conditions. The pre-ignition limit is formulated as the equivalence ratio ϕ in equation 2.4 which will vary between engine geometries and layouts. Other than engine design, the pre-ignition limit will also vary widely with CR and engine load as higher loads increase engine temperature, hence the risk of autoignition from hotspots [58] [59]. Whilst running the engine lean ($\phi \leq 0.5$) reduces the risk of abnormal combustion, the method reduces engine performance as stoichiometric, ideal combustion is not achieved.

$$\phi = \frac{A/F_{stoch}}{A/F_{real}} \quad (2.4)$$

In gaseous form, hydrogen has a very low volumetric energy density (VED) compared to other fuels. Although it has good mass energy density which is around 3 times higher than other fuels, volumetrically it is significantly worse which is not beneficial when the fuel needs to be in a gaseous state to combust. Compared to gasoline and

diesel which has a VED of 34 and 38 MJ/l respectively at 293K, hydrogen instead has a VED of around 0.010 MJ/l [60]. Due to this, and since hydrogen is gaseous at room temperature, it must occupy a much larger volume in the combustion chamber than vaporized gasoline. While the latter will take up around 1-2% of the combustion chamber volume, hydrogen gas will instead take up around 30% at stoichiometric conditions. The result of this will therefore yet again be that hydrogen engines must be made either bigger or with forced induction through turbo- / or superchargers since sufficient air will be needed to get good combustion and power output that can match conventional gasoline engines[9].

By utilizing a compressor to simulate a turbocharger Rouleau, *et al* [61] was able to run a modified gasoline engine at ϕ between 0.6-0.7 achieving a indicated thermal efficiency of 47%. Pre-ignition was suppressed by retarding the time of the inlet valve opening. However, as the authors pointed out the combustion characteristics are highly dependent on how the hydrogen-air mixture is formed and behaves inside the cylinder depending on SOI and intake valve timing.

2.3.3 Knock

Similarly to the previously mentioned pre-ignition another result from an uncontrolled combustion process is engine knock where the air-fuel mixture auto ignites ahead of the flame front creating a strong local pressure wave further igniting the mixture [62]. Knock is parameterized in knock intensity (KI) which describes the maximum peak-to-peak pressure differential [63]. Further, during the combustion of hydrogen, the lower energy required for combustion presents the risk of very high KI situations unofficially called "super-knock" [53]. As hydrogen has a higher autoignition temperature than gasoline and diesel this results in higher combustion chamber temperatures and increased temperature in hotspots. These hotspots then increases the risk of pre-ignition in the engine and also the risk of backfiring. The issue of higher knock intensities occurring in H₂ICEs is quite a substantial issue as the problem originates from the ambition to make engines as efficient as possible by increasing the CR.

Using a single-cylinder 0.6 litre SI engine with a modified intake manifold to function with hydrogen injection, Szwaja and Naber [64] conducted a study on the occurrence of knock and its intensity during hydrogen combustion. The results are divided into "light" and "heavy" knock where light knock is between 20-100kPa generated from a fast unstable spark. While light knock does not immediately damage the engine, prolonged usage is deemed to be dangerous as the continuous vibrations would reduce the life expectancy of the engine. Heavy knock, which instead is caused by unburnt hydrogen autoigniting in the end phase of combustion, regularly exceeds 200kPa but can in individual events reach above 1MPa causing major damage to the engine. The engine also utilized varying compression ratios showing that a CR lower than 7:1 reduces the occurrence of knock enough to be disregarded completely. However, while no actual power data is provided by Szwaja and Naber, it could be assumed that a reduction in CR to 7:1 would impact power significantly. Similarly Li, *et al* [65] reports how the connection between CR and ER can influence the

occurrence of knock. In the study where a CR of 11 and 17.5 were compared with varying ER, a higher CR results in a quicker increase of KI when ER is increased. This means the higher the CR the more sensitive to an increase in ER as when simulating CR 17.5 with an ER of 0.4 instead of 0.3 shows an increase from 0.6 to 6MPa in KI.

Lou and Sun [66] reported on how engine speed and backfire influenced the possibility of knock. Using a PFI 2.0 litre engine experiments were conducted on the relation between engine speed and knock occurrence. During higher speeds ($>3000\text{rpm}$) knock becomes more prone to appear as well as backfiring contributing by increasing internal temperatures in the cylinder. As the internal temperature increases the next cycle becomes more prone to pre-ignite causing a backfire again resulting in repetitive abnormal combustion.

2.3.3.1 Hydrogen properties

Methods to reduce the knock sensitivity of a combustion engine vary depending on the type of fuel and engine parameters. Gasoline engines usually rely on the fuel's octane rating where two ratings are often used, Researched and Motored Octane Number (RON and MON) [64]. These ratings define the resistance for knock in liquid fuels but are unfortunately not applicable for hydrogen because of the previously mentioned high autoignition temperature. Hydrogen's high autoignition temperature results in a high RON rating meaning a strong resistance to knock. In comparison, MON is tested under high engine speeds and loads with a preheated fuel mixture and variable ignition timing. Due to its low ignition energy and fast flame propagation, hydrogen instead scores a low MON rating meaning that the two contradict each other [67]. Instead, Methane Number (MN) which characterises gaseous substances' knock sensitivity is used [68] where a gas's sensitivity is rated on a scale from 0-100 where 100 represents methane which has the highest resistance to detonation and 0 represents hydrogen. In other words, this means that hydrogen is highly prone to produce engine knock.

2.3.3.2 Knock suppressing solutions

The most extreme cases of knock occur during stoichiometric A/F ratios at high load resulting in most H_2ICEs running with very lean mixtures [68]. Mechanically, retardation of spark timing is an option which decreases the thermal efficiency [69]. However, reduced efficiency means worse fuel economy and introduces risks from producing too high exhaust temperatures potentially damaging parts like a turbocharger.

A way to reduce the KI significantly is by the use of EGR [70]. EGR recirculates a fraction of exhaust gases back into the combustion chamber, thereby reducing the amount of oxygen which can combust and hence lowering the temperature of the combustion chamber. The research done by Koch, *et al* [38] demonstrates the benefits of EGR where the exhaust gas is circulated through a cooler before a part of the gas goes back to the inlet manifold and the rest to a turbocharger. With cooled

exhaust gases combined with air and fuel, the average flame speed is decreased, resulting in a reduced risk for knock to occur. Koch, *et al* claims that an EGR rate of 6% equals to an A/F ratio increase of 0.1 in terms of knock prevention, allowing for higher loads on the engine without encountering abnormal combustion.

Another suppression method of knock is Water Injection (WI) which similarly to EGR can increase the performance at high loads without encountering undesired auto-ignition. By injecting water into the intake manifold Mortimer, *et al* [37] explains how the flame propagation speed is reduced. Further, the injected water serves as cooling within the cylinder aiding to avoid hotspots. Comparing operation with and without WI, Mortimer *et al* reported that with the use of WI a 25% increase in power output was seen, allowing for a richer fuel-air mixture without occurrence of knock or pre-ignition.

2.3.4 Backfiring

As discussed briefly in section 2.3.3 knock, pre-ignition and backfiring are closely linked as cause of each other when engine temperatures rise. Yang, *et al* [71] studied ways to eliminate backfire by retarded ignition timing and water injection. The research established the connection between how pre-ignition and backfiring contribute to each other as both increase cylinder wall temperatures causing potential hotspot temperatures to increase as well. By postponing ignition timing the probability of pre-ignition can be reduced and water injection into the injection manifold eliminates the possibility of backfire. However, Yang *et al* points out that both overly postponed ignition timing and water injection reduces the brake thermal efficiency of the engine, as well as potential corrosive and lubricant issues which could occur during long-time use as a cause of the WI. Mohammadi *et al* [72] reports that on a DI one-cylinder engine injection during the intake stroke around 300 CAD BTDC prevents backfire but unfortunately reduces volumetric efficiency as the equivalence ratio is increased. The authors argued that injection during the compression stroke around 130 CAD BTDC is still preferred as the volumetric efficiency is much less affected by increasing equivalence ratio and knock is inhibited to an extent. This hence allows for higher Brake Mean Effective Pressure (BMEP) with an equivalence ratio of 0.8, doubling the achievable BMEP from the test with injection during the intake stroke.

With PFI as also discussed earlier is the risk of backfires entering the intake manifold present (illustrated in figure 2.5). As the hydrogen is injected during the intake stroke the fuel-air mixture ignites prior to the spark and can travel backwards from the cylinder into the intake potentially damaging the fuel injectors [73]. Thus, both engine longevity and performance are reduced as the hydrogen-air mixture is not detonated during the right ignition timing. With PFI being the less expensive option solutions like WI into the intake manifold are an option to avoid backfiring from harming the injectors but could potentially come with the price of performance reduction and longevity issues like discussed previously in section 2.3.3.2. It can however be avoided by the use of DI as the hydrogen instead is injected after the intake valves has closed.

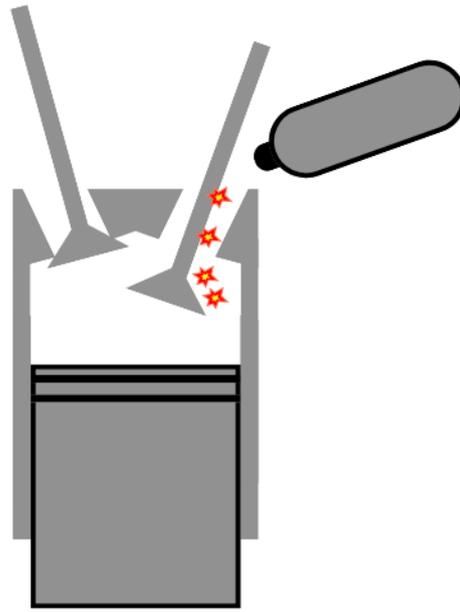


Figure 2.5: Illustration of backfiring event in a PFI.

A study by Lee *et al* [74] regarding experiments carried out on a one-cylinder engine further highlights the issues with hydrogen PFI. A hydrogen backfire occurs during combustion when the chemical reaction is too fast or the quenching distance too short, which causes the flame to propagate into the mixing region for the air and fuel. Due to this, a more hydrogen-rich air-fuel mixture will therefore increase the risk of backfire, which can cause damage [75]. Lee *et al* [74] performed tests with 115 cycles at 1500 rpm while advancing spark timing from TDC to 15 degrees BTDC. At the 100th cycle, as the spark timing had been advanced close to 15 degrees BTDC, backfire became more frequent concluding that ignition and injection timing must be controlled in order to properly run the engine.

In order to mitigate the backfiring issues specifically for PFI Gao *et al* [76] states that the main way to overcome the problem is to limit the amount of new air and hydrogen mix that can come in contact with hot gasses. For this, several engine adjustments can be made such as lowering the supplied amount of hydrogen and running in lean conditions or utilizing lower combustion temperatures by using ignition and injection timing that are not optimal for engine performance. This will, however, reduce the power output. Instead cooling the cylinder and piston with air before the fuel is injected is proposed, as this would potentially reduce the risk of backfire without severe power losses.

3

Methodology

This chapter explains the methodology used during this project from the literature study 3.2 to evaluation 3.4 of the engine technology today and what future hurdles remain.

3.1 Pre study

Initially, the project started with a pre-study in order to provide enough knowledge to fully understand further in-depth literature. This was done by utilizing lecture notes from the Chalmers course "Internal Combustion Engines" and "Powertrain Mechanics" together with recommended literature from the examiner.

3.2 Literature study

The comprehensive literature study was done through both qualitative and quantitative research, aiming to map out the complications which could arise with the use of hydrogen as a fuel in a combustion engine. The experiments and studies conducted previously could then be extensively evaluated and compared. As issues vary from fuel economy and combustion stability to emissions no experiment covered hydrogen engines in their entirety. To establish a full review of the situation of the engine today, information from all performed research was gathered where the key issues could be identified and the results from different studies could be cross examined see figure 3.1. Together with conducted experiments other reviews of hydrogen combustion were utilized as, while they focus on different areas, they do provide good insight and summation of the problems but also aid in finding gaps in knowledge.

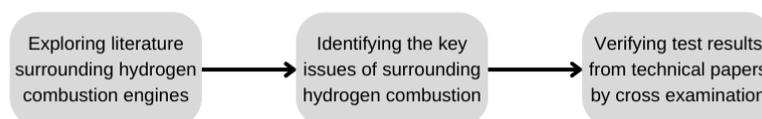


Figure 3.1: Approach of literature review

3.3 Data Collection

The data collected from various tests done from previous experiments surrounding the hydrogen combustion engine includes both data from real-life studies on engine rigs as well as numerical studies. This was done through the use of technical papers published by the Society of Automotive Engineers International (SAE) as well as Journal publications via the website Science Direct listed in table 3.1. Both of these forums are used for researchers to publish their studies and work and hence a good source for the literature review. To establish a good base of information search words were used to identify valuable sources. The search words used and how many sources were collected through them can be seen in table 3.2. As several sources can include two search words the total number is higher than the actual amount of sources used in the thesis.

Table 3.1: The main journals utilized throughout the thesis

Journal	No. sources
International Journal of Hydrogen Energy	24
Fuel	7
SAE International Journal of Engines	4

Table 3.2: The main search words used and their respective number of sources.

Search word	No. sources
Hydrogen internal combustion engine	37
Hydrogen pre-ignition	10
Hydrogen knock	15
Hydrogen injection	30
Hydrogen emissions	8
Hydrogen production	7

3.3.1 Source evaluation

In order to judge the information from all sources the information was constantly compared by finding relations between results from individual reports. This comparison of sources was further continued in the evaluation part of the thesis (section 3.4) as the results are used to formulate the main issues which still exist.

3.3.1.1 Outdated information

The research on hydrogen combustion engines has been going on for more than 100 years, which has resulted in certain experiment results and similar becoming outdated. The most obvious example are issues surrounding injection, as early hydrogen injectors struggled with the increased pressure needed. This means that not

all information is viable to use. With the mentioned matter of the constant improvements in hardware and software, the majority of results from technical papers were limited to research done during the past 15 years.

3.3.1.2 Biased information

To keep the probability of biased information low regarding the sources used in this thesis only full text technical or journal papers were used. However, since some research conducted has been done cooperatively between institutes and private corporations the risk of publication bias still exists [77]. Publication bias refers to the lower probability of papers producing unfavourable results compared to the probability of producing positive results which can occur as a study is conducted via a request from a company. The risk of publication bias in the sources used in this thesis is relatively low as the experiments conducted are not centred around a specific component produced by a company but rather studying an engine as a whole. Further, studies which lack interconnection between theory and results or source of errors have been avoided to not include inaccurate data.

3.4 Evaluation

The evaluation of the information collected in the literature study was done in Results, chapter 4 and finalized in Conclusions, chapter 5. The individual information gathered from different research was compared to each other. As the studies focus on various aspects the final conclusions may contradict each other depending on what the best way moving forward is. The evaluation is aimed to compare the information surrounding all aspects of the hydrogen combustion engine to provide a clear description of the progress and what challenges remain.

4

Results

4.1 Avoiding abnormal combustion

As documented in the Literature study (chapter 2), numerous studies have been conducted through the years concerning improving the stability of combustion. During the past 15 years, the general consensus has been to run hydrogen engines with an ER of $\phi = 0.5$ (equivalent to $\lambda = 2$) as this A/F ratio significantly lowers the risk of events such as pre-ignition and knock. However, some studies instead have aimed to run as close to the stoichiometric A/F as possible in order to extract as much power as possible. These experiments instead require knock suppressant measures such as the previously mentioned EGR or WI, which reduces flame propagation speed and provide lower in-cylinder temperatures. While use of WI and EGR works very well to suppress abnormal combustion it makes the engine more complex which may not be desirable although it might be the best solution.

The earlier research involving engine testing referenced in this thesis varies in insights as the papers focus on different issues within the subject of the hydrogen combustion engine. With the previously mentioned issue surrounding combustion becoming harder to keep stable at higher loads and speeds this presents the question of what kind of loads the engines have been subjected to in every study. In figure 4.1 the tests have been compiled showing at what RPM either part or full load have been used most frequently. The majority of tests for both part and full load are in between the range of 1000-2000 RPM with only a couple occasions where higher speeds have been tested. While a higher load usually increases the risk of abnormal combustion the engine speed also has an effect as higher engine speed results in higher temperatures and shorter mixing times. This is especially important for suppressing pre-ignition as its frequency can vary highly with engine speed and the best mitigation methods are not yet completely understood [54]. While these RPMs are within the regular operating range an engine would still need to be able to handle speeds high above 2000 RPM suggesting that the research might be lacking.

4. Results

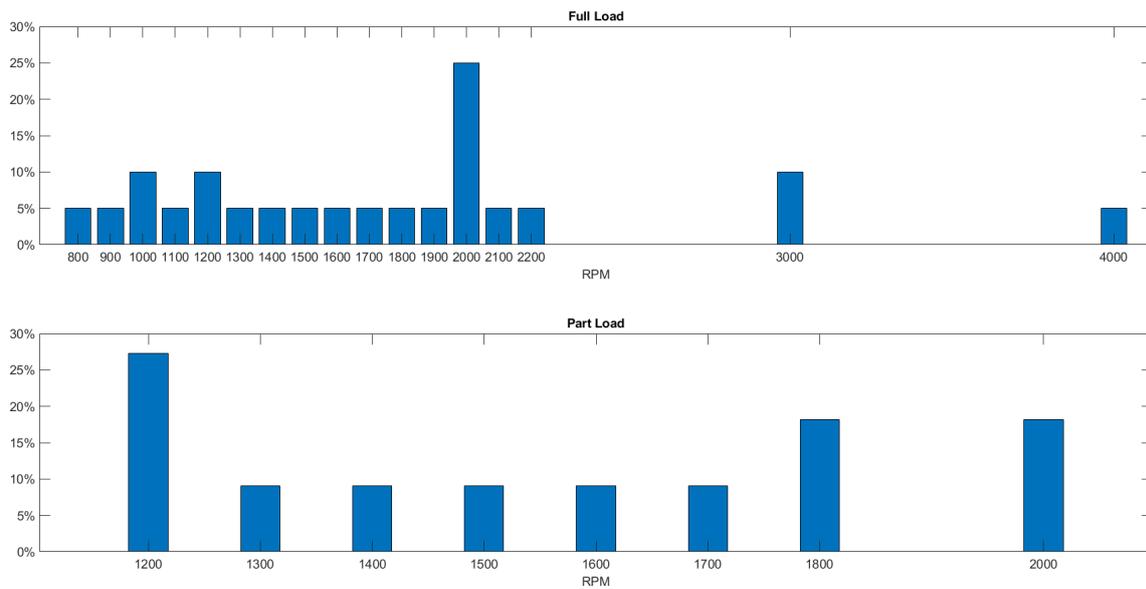


Figure 4.1: Distribution of load cases compiled from referenced papers

The optimum injection strategy does not seem to be a fact as of yet as PFI and DI are divided close to 50/50 between tests (see figure 4.2). With PFI promoting longer mixing time and hence a more homogeneous fuel-air mix it can suffer from backfire into the intake manifold. Together with risking damaging components such as injectors in the manifold flashback severely decreases the volumetric efficiency further as the flow is slowed into the cylinder. DI on the other hand eliminates the risk of backwards traveling backfiring as the intake valve is closed during injection but as a consequence has less time for mixing making homogeneous mixes harder to achieve. Generally, the use of DI still results in higher indicated mean effective pressure (IMEP) but is more complex compared to PFI. Thus an engine using PFI which can run with stable combustion but with slightly lower IMEP compared to a DI counterpart could still be attractive because of the ease of converting an already existing gasoline engine into a hydrogen engine. The highest recorded indicated thermal efficiency from the PFI and DI studies in this thesis are 38% and 47% respectively [58][69]. The DI referred to, however, utilized water injection which further makes the engine more complex and expensive as opposed to a PFI. PFI instead offers the ability of easier conversion from a gasoline-based ICE to hydrogen which still makes it attractive despite its lower thermal efficiency. While the CI engine referred to did operate with $\approx 45\%$ indicated thermal efficiency it was only able to operate during partial load. Together with the fact that recent research on compression ignited engines is very scarce, it does not seem to be a viable option in the near future.

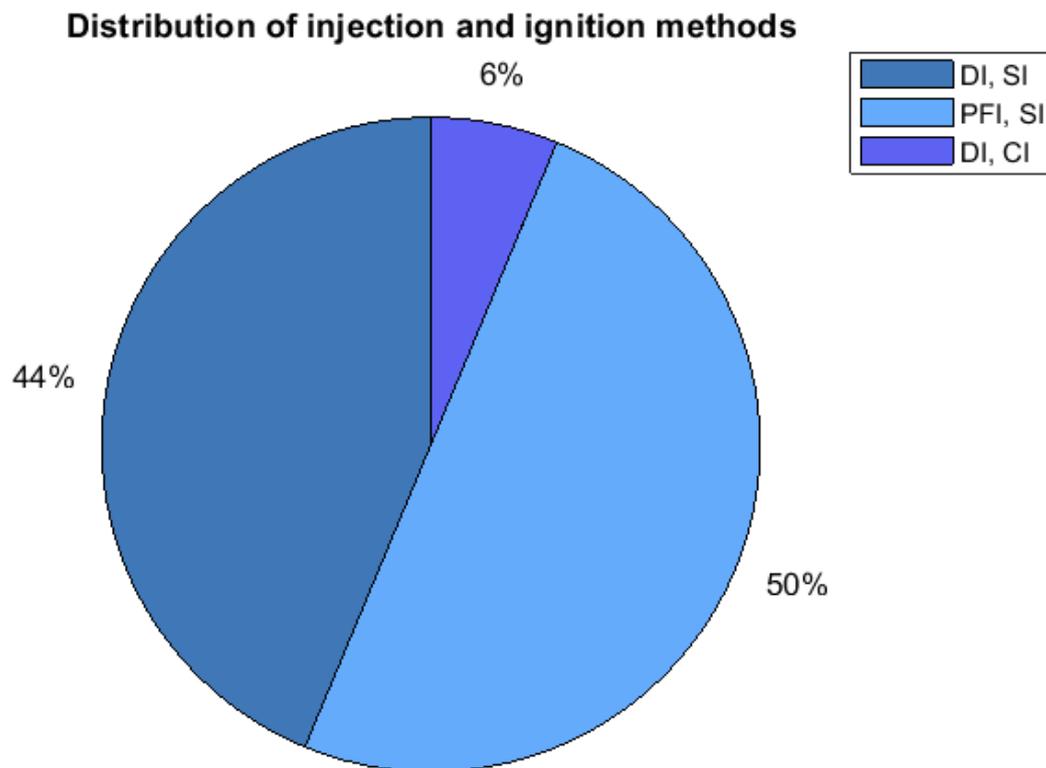


Figure 4.2: Distribution between chosen injection and ignition strategies between studies.

In figure 4.3 the five tests highest achieved indicated efficiency is displayed together with the respective IMEP/BMEP produced. PFI is as previously mentioned, around 10% worse in thermal efficiency compared to DI but still produces more power than the CI configuration. What also should be noticed is that the CI configuration had poor combustion stability with a maximum COV of 25% at high load as a result of knock.

4. Results

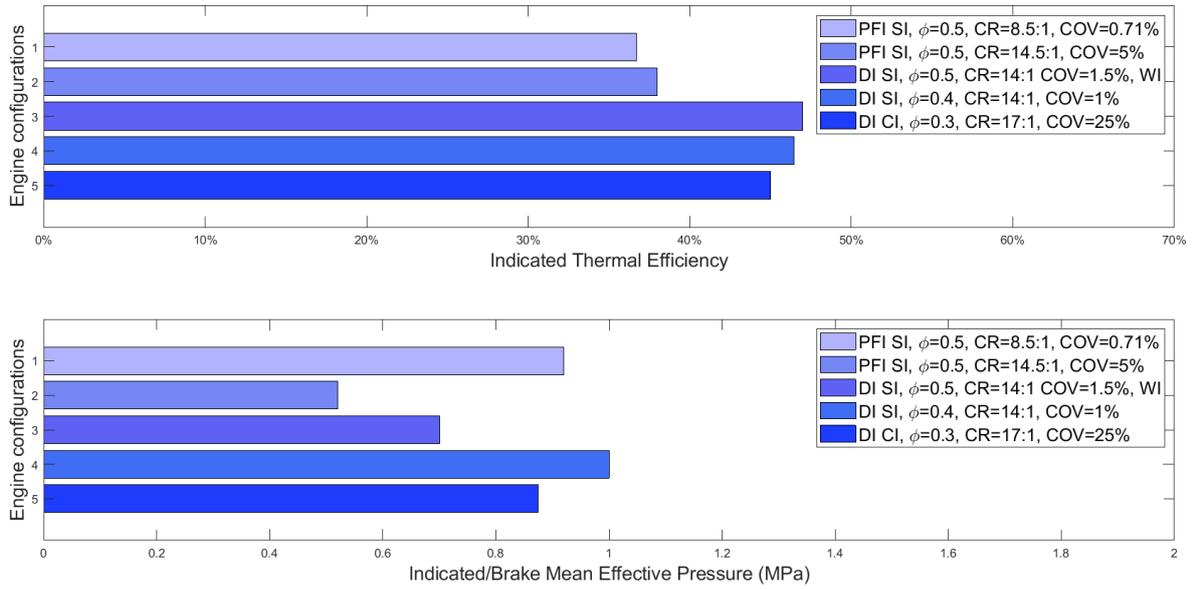


Figure 4.3: The two PFI and DI engines together with one CI engine which operate with the highest indicated thermal efficiency and the respective IMEP/BMEP produced by the engines [74][58][69][61][22]

The research surrounding the hydrogen combustion engine still has parameters of the engine to improve. With the need to develop an engine configuration capable of all load scenarios with high efficiency without the risk of abnormal combustion and unnecessary high emissions, different studies will focus on different subjects and still have quite some way to go. Factors such as combustion chamber and piston geometry have yet to be researched extensively. With a high sensitivity surrounding fuel-air mixing and hot spot-induced autoignition improvements in the geometry remain an important factor to develop. Likewise has very few actual tests in a vehicle been performed which may also present challenges.

4.2 Engine Power Density

The current major challenges of the hydrogen combustion engine are mainly its power limitations surrounding the risk of abnormal combustion. The engines suffer from issues such as improper auto-ignition of the fuel depending highly on A/F and during higher loads. While thermal efficiency is comparable to gasoline engines the hydrogen engine will not be able to provide as much power with the same displacement assuming that the parameters for the hydrogen engine would be set to avoid abnormal combustion. This presents the question, how much larger would a hydrogen engine be to function similarly to an everyday passenger vehicle and is the size feasible? In figure 4.4 the referenced studies achieved BMEP and IMEP are demonstrated. The reason for having both IMEP and BMEP is simply because of differences between technical papers and authors who document differently. With a max achieved BMEP of 1.215 MPa by Koch *et al* [38] it is about half as powerful as a normal passenger vehicle gasoline combustion engine. This would mean that twice the displacement would be needed in a hydrogen engine to be equivalent in power to a gasoline counterpart. This is while assuming that the gasoline and hydrogen engine's max torque is developed at the same RPM, otherwise the difference in displacement could differ slightly.

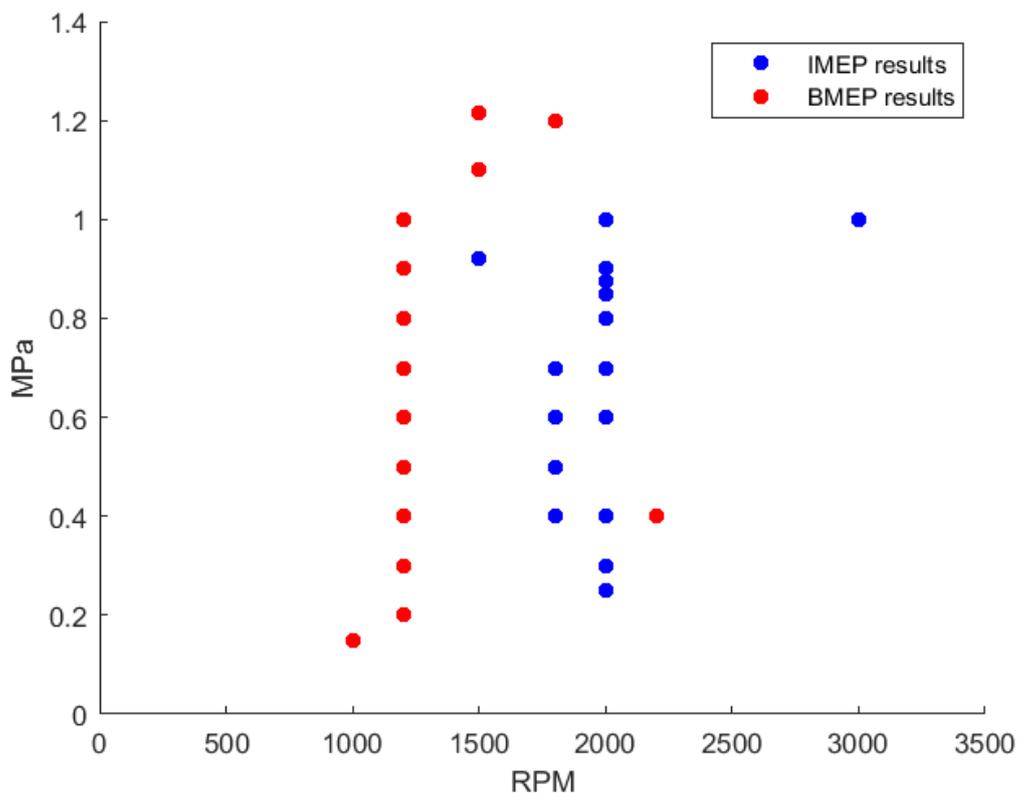


Figure 4.4: Distribution of measured IMEP or BMEP from referenced papers

In figures 4.5 the highest IMEP achieved for every ER ϕ is displayed. While in theory an equivalence ratio closer to the stoichiometric ratio ($\phi = 1$) would allow for a

higher load, the studies attempting this have been hindered by abnormal combustion resulting in lower IMEP compared to cases operating with $\phi \leq 0.6$. Further in figure 4.6 it is evident that the indicated thermal efficiency for $\phi < 1$ is roughly reduced by 10%. This poses the question of whether operating at the stoichiometric A/F ratio is even reasonable. With ϕ around 0.5 the risk for abnormal combustion is lowered significantly while producing more power at a higher efficiency.

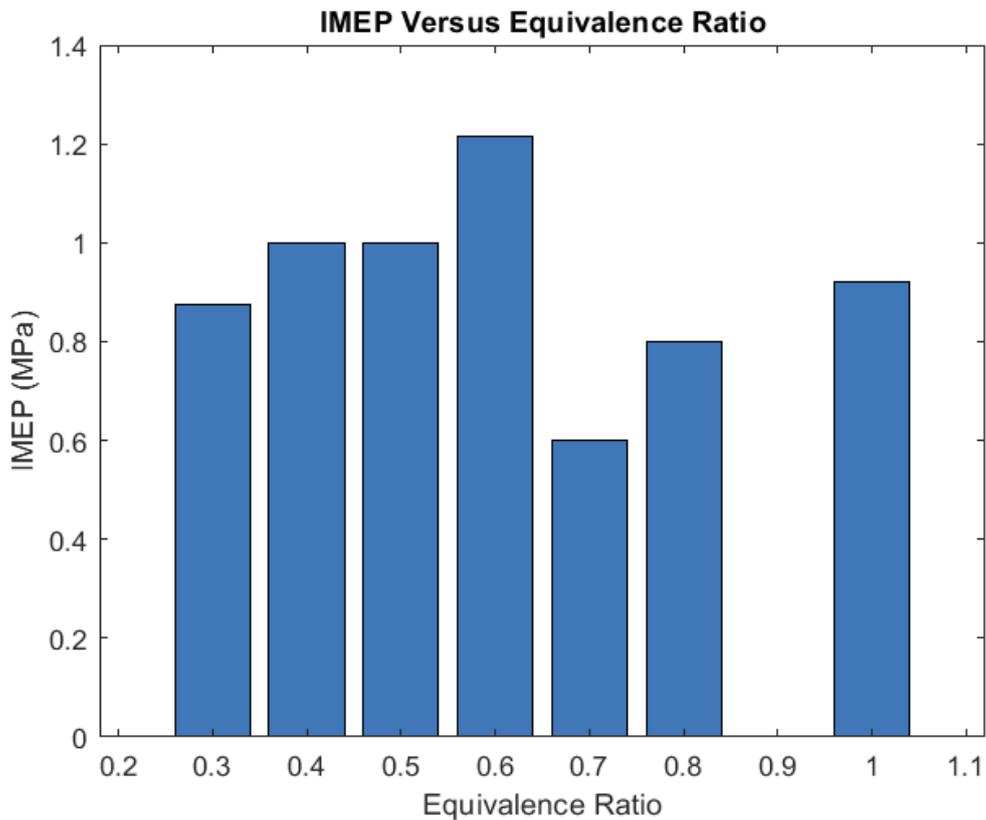


Figure 4.5: Highest achieved mean effective pressure at every equivalence ratio ϕ

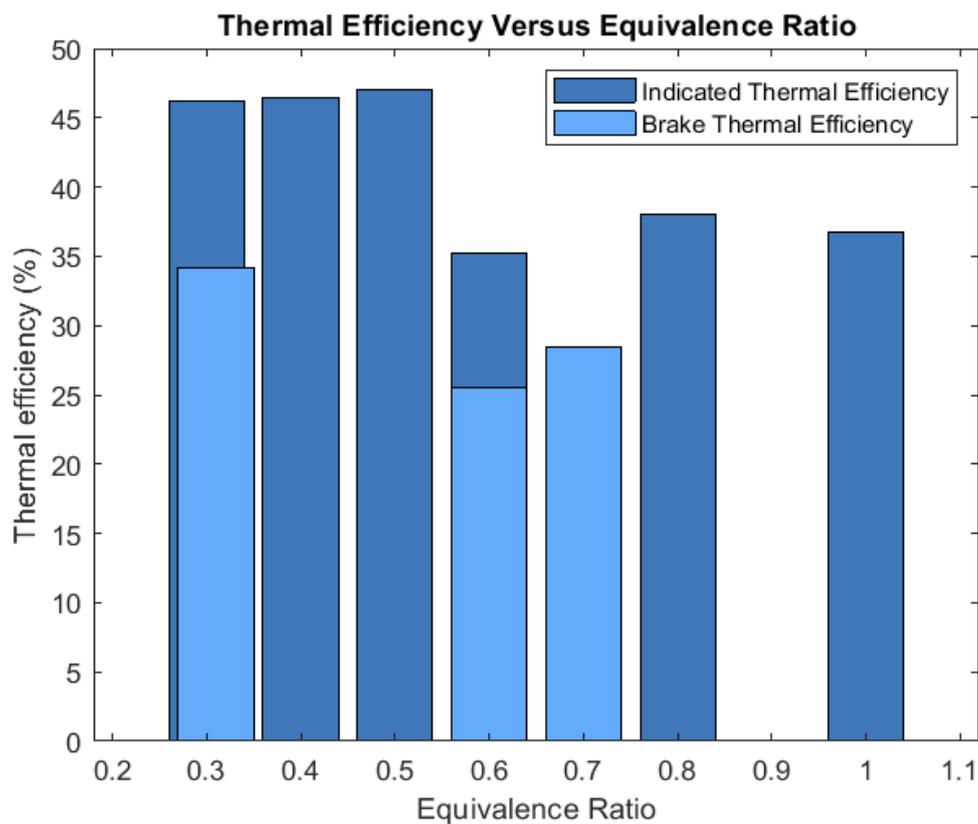


Figure 4.6: Highest achieved thermal efficiencies at every ER ϕ

With the previously mentioned required increase in engine displacement needed to produce power, another issue arises, namely air supply. Hydrogen's stoichiometric A/F is 34.2:1 which requires more than double the mass of air compared to gasoline combustion in order to achieve complete combustion without excess air. When lowering the equivalence ratio to 0.5 the amount of air is doubled once more meaning an A/F of 68.4:1. While most studies are done on a 1-cylinder engine ranging from 0.5-1 litre an actual full size engine would require huge amounts of air during operation. In addition, most engine rigs only simulate turbocharging by the use of compressed air whereas a real life engine with a turbocharger would be more complex as hydrogen exhaust gases carry less energy than the gasoline counterpart making it harder to spool up [2].

4.3 Emissions

While types of emissions from a hydrogen combustion engine are few compared to a gasoline engine the risk of high NO_X particulates is still present. The amount of NO_X emitted increases exponentially when going from a lean A/F towards the stochastic ratio. In figure 4.7 the distribution of chosen final equivalence ratios used by different studies which have been referenced in this thesis have been compiled where the majority (67%) of studies choose to run the engine lean ($\phi \leq 0.6$).

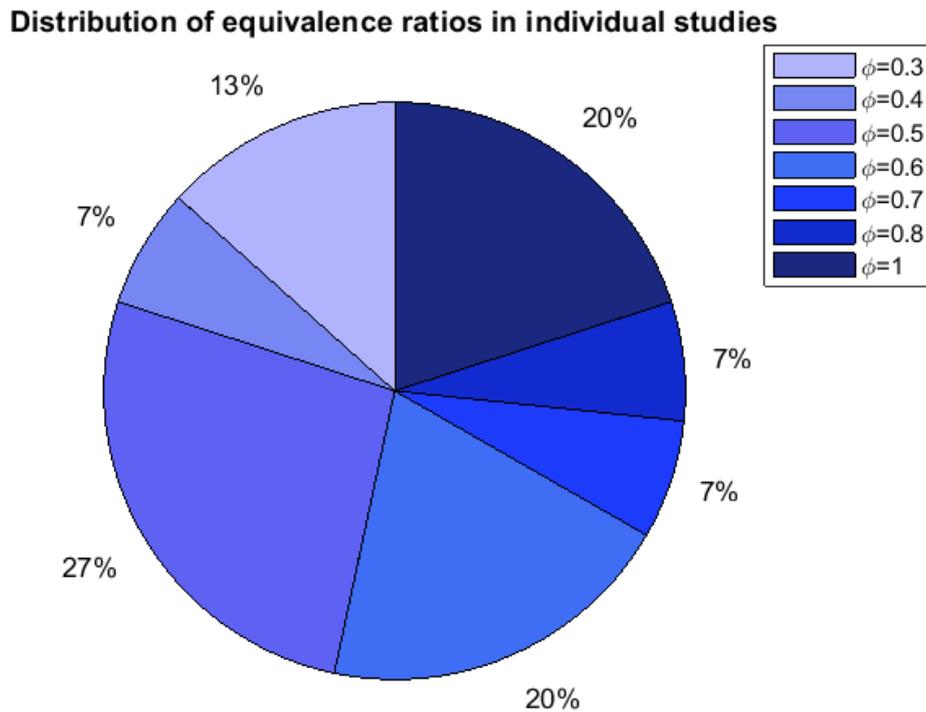


Figure 4.7: Distribution of equivalence ratio ϕ between studies referenced in this thesis

No study encompasses the entirety of the hydrogen combustion engine ranging from performance improvement, reliability and emissions presenting an issue where the research on emissions and performance can contradict each other. Dilution strategies such as WI or EGR have been proven to reduce NO_X formation but at the same time allow for higher achievable engine loads which instead increase NO_X making the decision on how to utilize the dilution methods harder. Regarding specific data on emitted NO_X between studies, this has been excluded as differences in engine specifications and documentation methods between technical papers result in a large margin of uncertainty when compared. In addition linking back to figure 4.1, with very few tests done at higher engine speeds (especially for high load) where temperature increases together with NO_X production it is difficult to estimate what emission numbers an actual vehicle would produce. What is possible to say, however,

is that with the superior performance at $\phi \leq 0.6$ the occurrence of NO_x emissions is not as large of an issue as operating at the stoichiometric ratio.

An immediate change to hydrogen combustion is also not feasible as hydrogen production with 95% still being grey production. As 1 ton of hydrogen equals to around 7-15 tons of CO_2 the total emissions would increase tenfold for the transport sector should all vehicles shift to hydrogen propulsion. However if, electrolysis production increases hydrogen could be more reasonable as a fuel.

4.4 Engine Specifications

While compiling the studies a lot of different engine parameters were presented to get the best running and performance from the engine. Analyzing this, what was looked at was what could be optimized and changed on the engine which included looking at timing for injection and ignition as well as the effect of differing CRs.

4.4.1 Engine geometry

The vast majority of studies referenced in this thesis have been conducted on one-cylinder engines with displacements varying between 0.5 to 2.5 litres. It also appears to be favoured to utilize slightly undersquare bore-to-stroke ratios which is understandable considering the limitations with engine speed. The use of an oversquare engine would also mean a larger area to achieve proper air-fuel mixture as well as higher heat losses through the piston. In terms of other geometries experimented with there are few. With a large challenge being correctly mixing air and fuel, it is surprising that so little research in geometries such as cylinder heads or injector nozzles has been done. Repeating what was described in section 4.1 however, is that research on larger displacement engines is scarce. Many studies have utilized compressed air to simulate forced induction and in some cases additional cylinders which did not operate with hydrogen but via a generator have been used to power a turbocharger [69].

4.4.2 Fuel Injection

As discussed earlier in section 4.1 are issues present with both PFI and DI. In order to further control the injection for both systems and avoid these issues the injection has to be timed properly. The differing SOI timings for both injection types collected are shown in 4.8. The reason that the total amount of bars in the figure is quite few is due to many studies utilizing variable injection timing.

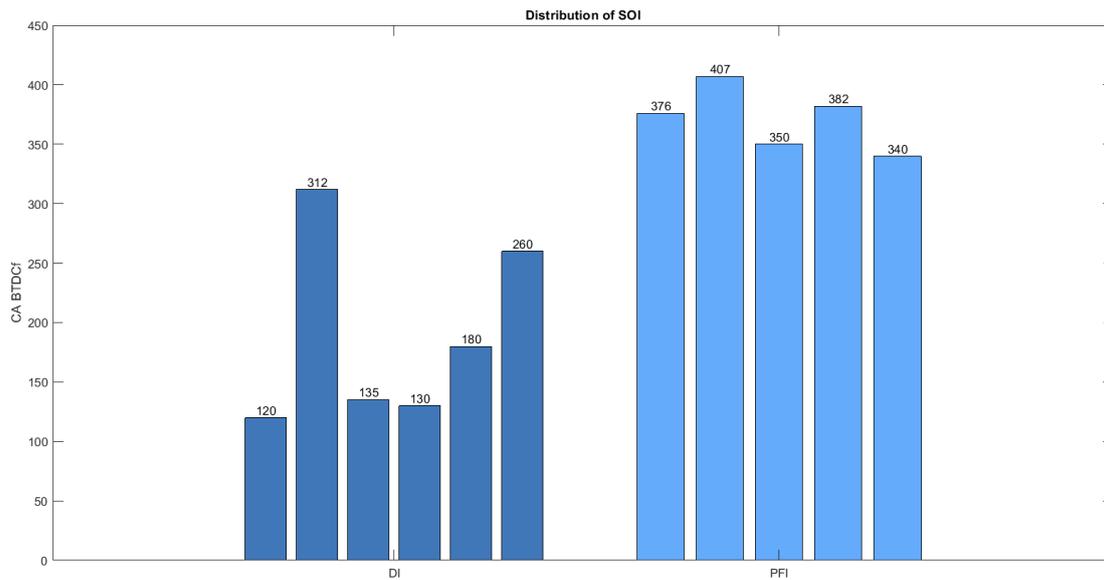


Figure 4.8: Distribution of SOI between studies based on CAD before top dead centre firing (BTDCf)

The split in CAD between PFI and DI in figure 4.8 is clear and is caused by the difference in fuel delivery for the two systems. PFI relies on the piston to pull both air and fuel into the cylinder during the intake stroke. The SOI of the technical papers ranged between 340 to 407 CAD BTDCf which is around where the exhaust stroke is ending and the intake stroke is starting. For DI, however, the spread of SOI varies substantially. While DI usually has the possibility to inject later in the engine cycle with a majority of SOI occurring between 120 and 180 CAD BTDCf some outliers at 260 and 313 CAD BTDCf are visible in figure 4.8. For the former, injection takes place during the compression stroke but not too close to ignition CAD as this would require very high pressure injectors and would deteriorate the mixing of the air-fuel mixture. From the studies, it was assumed that the closest possible injection would be at 88 BTDCf for sufficient mixing, although more studies have to be performed regarding this. For the latter cases, the injection will instead occur at different points during the intake stroke with the main reason for this being that it greatly increases the mixing time of the fuel and air which can be very advantageous at higher engine speeds. This does, however, come with an issue as volumetric efficiency is decreased during the intake stroke as well as the risk of flashback is present similarly to a PFI. Together with these risks and since the majority of studies have concluded to run with later SOI:s it may be assumed that optimal SOI is during the compression stroke.

4.4.3 Ignition

Regarding the results from section 4.1 there seems to be an insufficient amount of studies conducted on CI engines. With the challenge of very high combustion instability, the vast majority of researchers have chosen to utilize SI instead. Compared

to injection, the ignition timing will be the same regardless of the injection strategy. Instead, timing needs to be based on other engine parameters especially CR and ER as well as engine load and speed. Al-Baghdadi [25] through simulation provided a general idea of how these parameters affect optimal timing which has been visualized in appendix A. It can be seen that depending on the load, timing ignition would either be over an earlier range (18 to 26 CAD BTDC) for lower loads or over a later range (10 to 18 CAD BTDC) for medium to full loads for the best result. The other ranges that also need to be considered are for differing CRs and engine speeds. Going from low to a higher engine speed the ignition timing has to occur earlier as the engine is moving at a faster rate. While this breakdown in appendix A between parameters was done through simulations and can vary heavily between engine configurations and geometry it provides an overview of the available window for optimal ignition timing. Further Al-Baghdadi has no real test data to correlate the simulations as of yet. Similarly to what was mentioned in section 4.1 however, data with engine speeds higher than the regular working range is lacking.

The largest challenge around ignition in the H₂ICE is the issue surrounding pre-ignition. To suppress pre-ignition the ignition timing can be retarded closer to TDC however, at higher engine speeds where the occurrence of pre-ignition increases the ignition timing has to occur earlier to maintain efficiency and power. Since the two circumstances contradict each other a choice would have to be made to either maintain low engine speeds or introduce another method of pre-ignition suppression such as WI.

4.4.4 Compression

The distribution of CRs can be seen in figure 4.9. While the range of CR is quite wide the vast majority of papers have conducted studies with ratios between 8:1 to 14:1. While several studies operating with CRs above 14:1 also have been performed, those tests have either not been done at full load or with reasonably low power figures (example: 0.6MPa IMEP [14]).

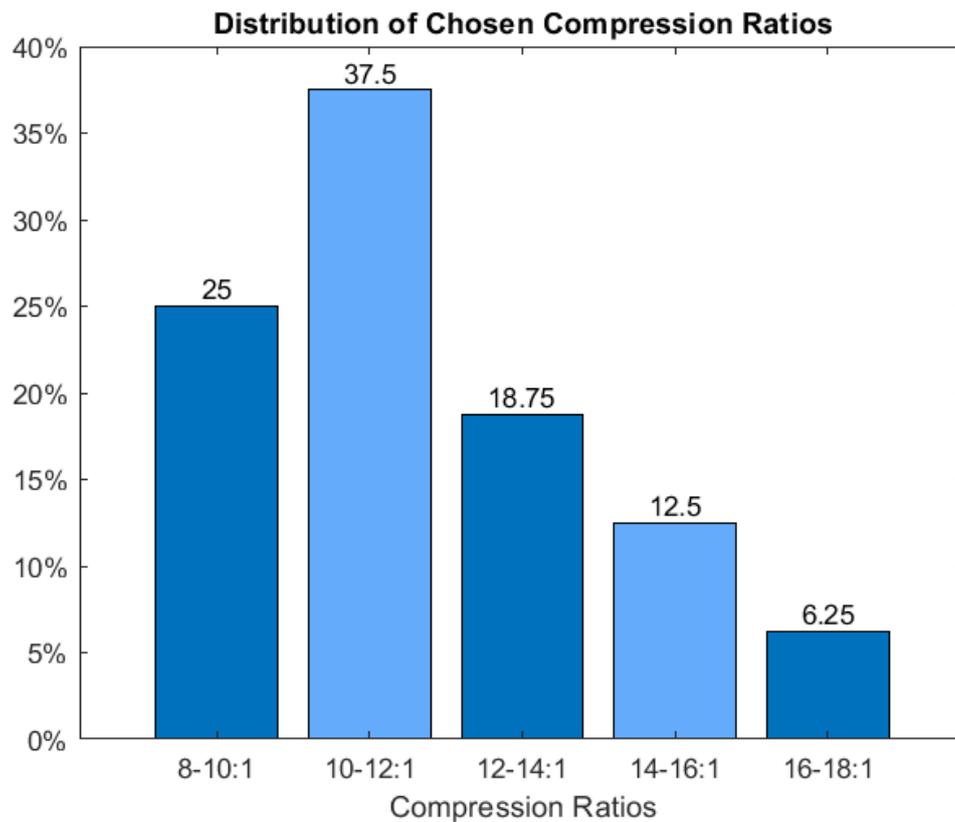


Figure 4.9: Distribution of CR between studies

While the decision on whether PFI or DI is optimal remains, the choice of CR seems to be fairly set with PFI operating regularly around 10:1 and DI slightly higher around 12:1. Since CR has a large influence on overall power produced small increases if possible could prove to be beneficial for future work if knock and pre-ignition methods such as WI and EGR would be explored further.

4.4.5 Engine Speed

As has been discussed throughout the results chapter the question surrounding what engine speeds are feasible is prominent. The majority of full and part load tests have been conducted at speeds lower than 2200 RPM (figure 4.1) resulting in a quite large unknown surrounding what speeds the engine should be limited to. WI has proven to suppress pre-ignition but has only been tested with high ER:s close to 1 which has caused other issues as a cause of low ignition energy. However, little research has yet tested the combination of WI together with a lean A/F which could potentially allow for higher speeds. Should the H₂ICE instead have to be operated with a specialized gearbox to keep engine speeds low the impact on the engine concept as a whole would take quite a large blow as the motivation for the H₂ICE is its large similarities to today's fossil-fueled ICE.

5

Conclusions

In this thesis, the situation surrounding the hydrogen internal combustion engine was reviewed through a literature study which both described the different engine configurations that can be used and also the existing challenges together with the sources' own conclusions. Data from engine tests 15 years old or newer were collected to then evaluate which areas researchers have reached a consensus on and which challenges remain. This was done by comparing the results from all the engine tests to see what conclusions could be drawn based on the test data from the studies. While progress has been made during the past years there still are challenges which need further investigation. Below the four main factors are listed.

- **Abnormal combustion:** Troubles surrounding abnormal combustion is still present in all studies limiting load range. The majority of tests have also been focused around the regular working engine speed range (1000-2000RPM) with very few actually conducting experiments on higher speeds. Studies utilizing methods to suppress abnormal combustion have done so while trying to operate at the stoichiometric A/F limiting achievable load instead of using leaner mixtures.
- **Power:** The highest achieved BMEP by any study is 1.215MPa which is around half of a normal passenger vehicle's. Ergo, a hydrogen engine would need twice the displacement to a gasoline engine in order to produce the same amount of power. A larger displacement also means more oxygen is required together with an equivalence ratio of $\phi = 0.5 - 0.6$ posing issues of air supply. With few actual driving demonstrations, the question becomes how an actual engine with much larger displacement compared to regular 1 litre test engines will function.
- **Emissions:** Research on emissions has been divided from research on performance as while NO_X production can be lowered to minimal values this affects the performance and vice versa. Hydrogen production today is also not done in a sustainable way. meaning that a shift to hydrogen before the vast majority can be produced by green methods would actually increase the total global emissions.
- **Engine geometry:** While studies seem to be agreeing on utilizing an undersquare bore-to-stroke ratio very little other research on subjects such as injector and piston geometry has been performed. With mixing proving to still be an issue, future studies on geometry improvement will most certainly

5. Conclusions

prove to have a positive effect. Additionally, researchers are divided almost 50/50 on PFI and DI. This is most likely because of the complexity and cost differences making researchers choose depending on the budget available.

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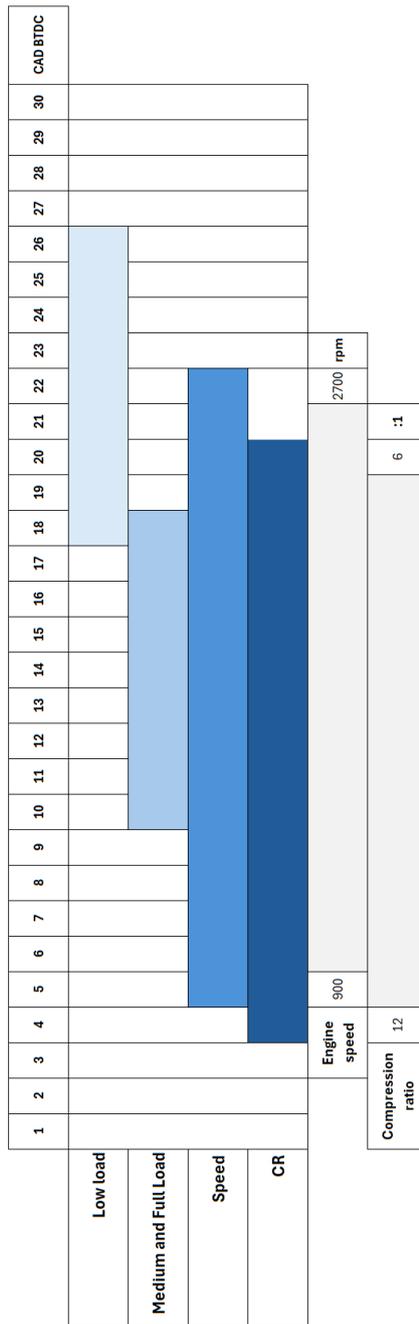
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Appendix 1



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