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MSc Motorsport Engineering

The Feasibility of Powering an Internal
Combustion Engine on Hydrogen and its
Optimisation Through Combustion Modelling

Research Proposal

Postgraduate Research Methods & Professional
Development

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Acronyms

ICE – *Internal Combustion Engine*

H₂ICE – *Hydrogen Internal Combustion Engine*

EV – *Electric Vehicles*

FCV – *Fuel Cell Vehicles*

SI – *Spark Ignition*

LBE – *Lean Burn Engine*

NA – *Naturally Aspirated*

MIE – *Minimum Ignition Energy*

NO_x – *Nitrous Oxide*

CO - *Carbon Monoxide*

CO₂ – *Carbon Dioxide*

HC – *Hydrocarbons*

N/A – *Naturally Aspirated*

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1 Introduction

Ever since the dawn of the internal combustion engine there has been the underlying issue of air pollution emissions due to the incomplete combustion of carbon-based fuels having an adverse effect on human health, air quality & global warming. In 2019 a new legislation was signed, committing the UK to a legally binding target of net zero emissions by the year 2050 (GOV.UK, 2019), as part of this incentive PM Boris Johnson vowed to cut emissions by 68% by 2030, to help achieve this target Johnson has announced the plans to wholly ban the sale of new petrol and diesel vehicles in the UK by 2030 (Harrabin, 2020). Furthermore, the world of motorsport is also striving for a more sustainable future with Formula 1 announcing their plan to become carbon neutral by 2030.

“Environmentally friendly cars will soon cease to be an option... they will become a necessity” this was stated by Fuijo Cho a Honorary Chairman of Toyota at the North American International Auto Show in 2004 and now, 17 years later this statement could not be any more relevant. In recent years, Hybrid, EV and Fuel-Cell technology has come on leaps and bounds, F1 currently utilise hybrid technology and the BTCC and WRC have both announced they will be implementing hybrid technology for the 2022 season. Furthermore, the FIA already run EV championships with Formula E & MotoE and there is also the HYAZE League which is planned to launch in 2023 using only hydrogen fuel cell vehicles (Boxall-Legge, 2020).

Whilst all of this is great progress for a more sustainable future, the technology and infrastructure that would be required to completely convert the world of motorsport to FC or EV power is not without its limitations. For example, battery-powered race championships are limited on the vehicles ability to compete over a race distance without having to save energy, and the technology and infrastructure involved for both EV and FC powered race championships will prove expensive, although this may not be an issue for the higher-end of motorsport, at the lower levels such as the British Superbike Championship and even at club level, neither EV or FC powertrains may be a viable or affordable alternative for years to come.

This paper proposes a feasibility study of modifying the already existing and well-established technology of an ICE to combust a more efficient and cleaner fuel such as hydrogen, the most abundant element in the universe which produces no CO₂. This is to be done by computationally modelling an ICE powered on hydrogen and then making the appropriate modifications for optimal performance and efficiency. The engine in question is from a four-stroke, 250CC, Naturally aspirated, single cylinder, 2014 KTM RC250R Moto3 which competed in the 2019 BSB Motostar championship and was kindly donated to the author by SymCirrus Motorsport.

1.1 Aims & Objectives

The aim of the project is to develop a theoretical model for combustion performance and emission characteristics of a Moto3 high-performance race engine to be powered on Hydrogen. The project will focus on the combustion processes within the cylinder and not on the other areas required for a hydrogen conversion such as the cylinder head components, fuel storage, crankcase ventilation etc.

1.1.1 Objectives

- Remove required components from the KTM RC250R Moto3 engine to take the required measurements, bore, stroke etc.
- Generate CAD model and motion simulation of engine with SolidWorks.
- To create a combustion model within MATLAB investigating cylinder pressure data and a NOx model consisting of a lean-burn model and a stoichiometric with EGR model.
- Combustion modelling in ANSYS Forte, investigating engine parameters and their effects on performance and emissions.

2 Industrial Relevance

The hydrogen internal combustion engine (H₂ICE) dates back as far as early as 1807 when Francois Isaac de Rivaz built the first working model (Kantola, 2017). In 2020 the EU initiated the “*European Clean Hydrogen Alliance*” and since then the H₂ICE has become increasingly in the spotlight in the automotive industry’s debate on zero-emission powertrain solutions (Andree, 2020). German company FEV is currently developing H₂ICE’s as a robust and cheaper alternative for zero CO₂ transport, they believe that fuel cell development is still within its early stages and that utilising a H₂ICE is a more viable current alternative that can be implemented at a much quicker rate under the already available production infrastructure (FEV, 2020).

The main areas for development of H₂ICE’s are as follows:

- | | | |
|----------------------------|-------------------------------------|-------------------------------|
| ➤ Fuel-Carrying Components | ➤ Ignition & Fuel Injection Systems | ➤ Engine Control |
| ➤ Crankcase Ventilation | ➤ Charging | ➤ Exhaust Gas After Treatment |

Table 1 Hydrogen ICE's Key Development Areas (FEV, 2020)

As previously stated, hydrogen is the most abundant element in the universe making it a perfect renewable source of energy for a zero-carbon future and has been recognised as an alternative fuel under the energy policy act since 1992 for its clean and flexible energy source, energy efficiency and power in comparison to fossil fuels and it produces almost zero emissions (TWI, 2021). Hydrogen is virtually always found as part of another compound such as water or methane, H₂O and CH₄ and much therefore be separated into pure hydrogen H₂. Hydrogen can be produced from varied resources which include biomass, fossil fuels and electrolysis with electricity (US Department of Energy, 2016).

3 Literature Review

For an explanation on the fundamentals of the four-stroke cycle and otto-cycle please see Appendices 9.2 and 9.3.

3.1 Combustive Properties of Hydrogen

3.1.1 Flammability Range

During the design process of a combustion chamber the flammability parameters of the fuel need to be considered. A combination of a fuel and an oxidant can provide rise to a self-propagating flame if the oxidant-fuel ratio is inside a specific range (Ali Nassimi, 2017), this range is depicted by the lower and upper flammability limits (LFL & UFL) expressed on a scale of 0-100%. The LFL is the smallest fuel concentration that is capable of self-propagating a flame anything below this point the mixture will be too lean to combust, whereas the UFL is the most amount of fuel concentration capable of self-propagating a flame, anything above this limit will be too rich to combust.

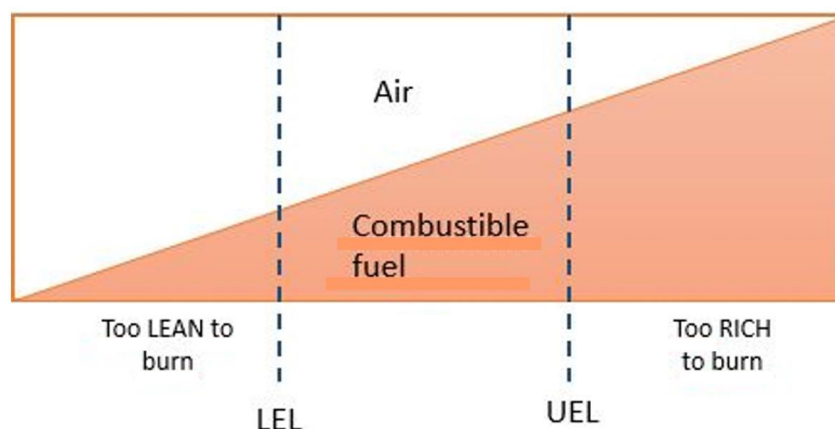


Figure 1 Combustible Fuel Diagram (Aisyah, 2016)

Hydrocarbon liquids are usually regarded as having a very narrow flammability range, most are between 1-12% (Firehouse, 2005). Literature states that range of Octane is 0.92-6.4%, whereas hydrogen has a much wider flammability range of 4-75% (Ali Nassimi, 2017). Furthermore, this wider range would allow hydrogen to be combusted in an ICE over a wider range of fuel-air ratio's in comparison to petrol.

Lean combustion is one in which the amount of fuel is lesser than that of the theoretical stoichiometric ratio, different fuels need varying volumes of air for stoichiometric conditions. Since stoichiometry can be defined in terms of mass or moles, a normalised value is best for comparing fuel forms (Therkelsen, 2016). The equivalence ratio – ϕ is the ratio of the fuel mass flow rate to the air mass flow divided by the exact same ratio at stoichiometric conditions and the relative air-fuel ratio - λ is the equivalence ratio's inverse, these are two examples of normalised quantities for comparison across fuel forms (Therkelsen, 2016). When $\phi < 1$ the combustion is considered lean and when $\phi > 1$ the combustion is considered rich. As a result of hydrogens wide flammability range an ICE could run on a lean hydrogen-

air mixture, meaning it would be relatively easy to get an ICE to start on hydrogen, also, in general fuel economy is better and the combustion reaction is more complete when an ICE is powered on a lean mixture. Furthermore, with a lean burn engine (LBE) the final combustion temperature tends to be lower, there is an array of benefits to this in terms of both heat transfer and heat rejection to the exhaust. Consequently, in a lean burning H_2 ICE the amount of work done during the expansion stroke is relatively large as a result of this lower cycle temperature, resulting in a proportionally higher thermal efficiency. Additionally, the lower temperature reduces the amount of pollutants such as NO_x emitted in the exhaust, but a LBE is not without its limitations as a lean operation can significantly reduce the power output due to a reduction in volumetric heating value of the oxidiser-fuel mix, thus a compromise must be met, literature states that for hydrogen it would be required to confine engine operation to around $\phi - 0.65$ to reduce NO_x emissions to acceptable levels (Florida Solar Energy Center, 2014).

3.1.2 Flame Temperature & Speed

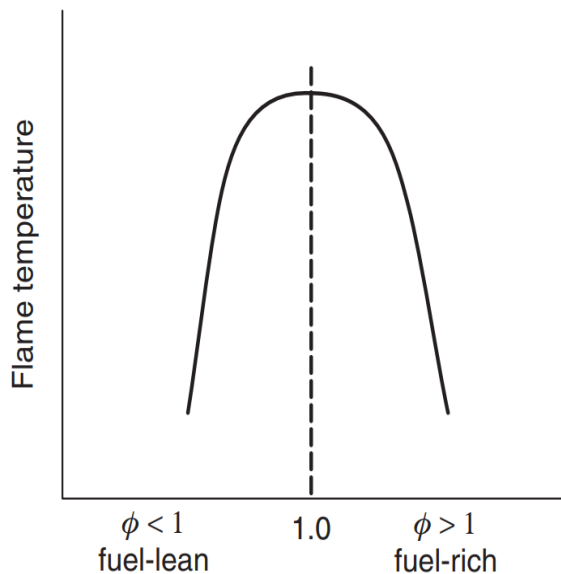


Figure 2 Variation of Equivalence Ratio on Flame Temperature (Glassman, 1977)

The adiabatic flame temperature is defined as the temperature attained when the combustion chamber is well insulated with no heat loss. The peak adiabatic flame temperature occurs at an equivalence ratio of 1, meaning the higher or lower ϕ is from 1 the flame temperature will decrease as demonstrated in Figure 2 (Glassman, 1977), the flame temperatures of hydrogen and petrol can be found in Appendix 9.4.

The rate of flame travel in a SI combustion chamber is the main factor controlling the pressure increase rate and is an important influence on engine performance. The SI engine combustion rate is predominantly influenced by the geometry of the combustion chamber and the

flame speed of mixture burn-up (Ali Ghanaati, 2015). The flame structure model accounts for the laminar flame speed, turbulent flame speed, and the transition between these two as demonstrated in the subsequent figure where this transition takes place as the flow velocity increases.

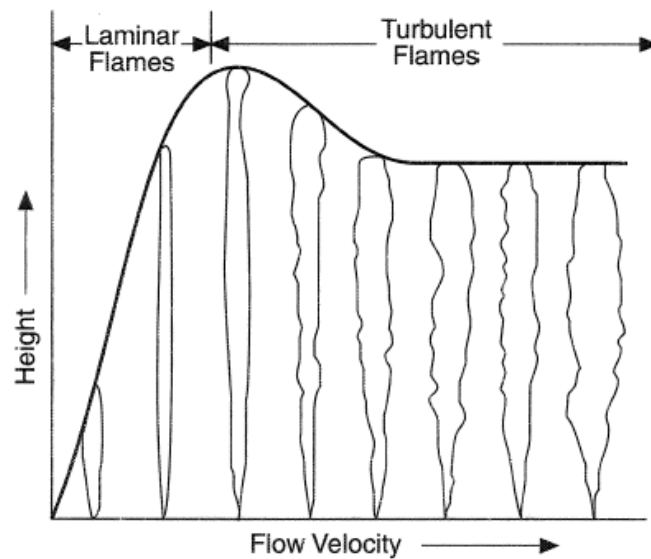


Figure 3 Change in flame type with increase in gas velocity (Hottel, 1940)

Stoichiometric combustion of a H_2 ICE has a high flame speed and is almost an order of magnitude higher than that of petrol. Literature states that taking atmospheric conditions into account; P – 1.013 Bar and T - 293.15 K the laminar flame speed of stoichiometric hydrogen combustion is seven times faster than that of petrol and even during lean combustion, the flame speed is fast enough to avoid efficiency losses caused by delayed combustion (Rahman, 2018). Consequently, these faster flame speeds mean hydrogen engines can more closely approach the thermodynamically ideal engine cycle (College of the Desert, 2001). Finally, it is worth noting that at leaner hydrogen-air mixtures, the flame speed begins to considerably decrease.

3.1.3 Ignition Energy & Autoignition

Ignition is defined as the process of providing the energy that is necessary to initiate a combustion process. Hydrogen has an exceptionally low ignition energy, an article from the Journal of Physics: Conference Series, states that the minimum ignition energy (MIE) of hydrogen is just 0.019 mJ, whereas petrol is usually on the order of 0.1 mJ (Kumanmoto, 2011). This low ignition energy allows H_2 ICE's to ignite lean mixtures and ensures prompt ignition. On the other hand, the low ignition also implies that hot gases and hot spots on the cylinder will serve as sources of ignition, generating the issue of pre-ignition and backflash (College of the Desert, 2001). Pre-ignition is the phenomena where the hydrogen charge is ignited after the intake valves close, but before the spark fires and backflash is where the fresh charge of hydrogen ignites before the intake valves close (Xiaoguo Tang, 2002). One of the main problems with running a H_2 ICE is preventing this as the wide flammability range means that almost any hydrogen-air mixture can be ignited by a hot spot.

Autoignition takes place when a mixture of vapours or gases ignites spontaneously with no external ignition source, after reaching a certain temperature where the rate of heat evolved from the vapours or gases rises past the rate of heat loss to the surroundings (Manha, 2009). The autoignition temperature

of hydrogen is 773.15K, this is significantly larger than that of petrol which is 519.15-553.15K (Engineering ToolBox, 2003). The autoignition temperature is an important factor in determining the compression ratio of an ICE, this is because the temperature rise during the compression stroke is proportionate to the compression ratio (College of the Desert, 2001), and the higher autoignition temperature of hydrogen permits a greater compression ratio to that of a petrol engine, more information on the compression ratio can be found in Appendix 9.5. The temperature increase in the system can be expressed as:

$$T_2 = T_1 \left(\frac{V_1}{V_2} \right)^{\gamma-1}$$

Equation 1 Final Temperature (College of the Desert, 2001)

Where: T_1 – Initial Temperature, T_2 – Final Temperature, V_1/V_2 – The compression Ratio & γ – Ratio of Specific Heats

The specific heat ratio of a gas is the ratio of the specific heat at constant pressure denoted as C_p to the specific heat value at constant volume C_v (Miller, 1996). The higher the ratio, the higher the thermodynamic efficiency and since this ratio is directly related to a fuels molecular structure, where the less complex the higher the value, hydrogen which has the molecular structure of H_2 is much simpler than that of petrol and thus, has a higher specific heat ratio.

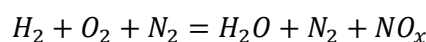
Hydrogen	Petrol
$\gamma = 1.4$	$\gamma = 1.1$

Figure 4 Specific Heat Ratio of Hydrogen & Petrol (College of the Desert, 2001)

Finally, it is worth noting that literature shows that if the compression ratio is lower than a certain value, the increase of specific heat ratio makes the work output and the thermal efficiency higher, but if the compression ratio goes past a certain value the increase of specific heat ratio will cause the work output and thermal efficiency to decrease (Ebrahimi, 2010).

3.2 NO_x Emissions

As previously discussed, one of the many benefits of hydrogen as an alternative fuel is that it has zero carbon content as its chemical formula is simply H_2 . Therefore, any carbon-based emissions are eliminated such as, CO, CO₂, and soot. Thus, the only harmful combustion by-product is NO_x (Ho Lyung Yip, 2019). NO_x is produced within the cylinder during the combustion process as a result of the high temperatures causing some of the nitrogen in the air to combine with the oxygen and can be expressed as:



Equation 2 Products of Hydrogen Combustion with Air (College of the Desert, 2001)

The subsequent two graphs display the emissions of a H₂ICE and of a petrol-powered ICE plotted against the equivalence ratio. It shows that the only emission produced by the H₂ICE is NO_x as opposed to the petrol engine which also generates CO and HC. Furthermore, the trend of NO_x decreases in a similar fashion for both engines. However, with the petrol engine there is a compromise as CO and HC emissions begin to increase as the equivalence ratio drops below a certain level. Also, for reasons previously explained the H₂ICE can run a leaner fuel-air mixture, visually demonstrated in the following graphs.

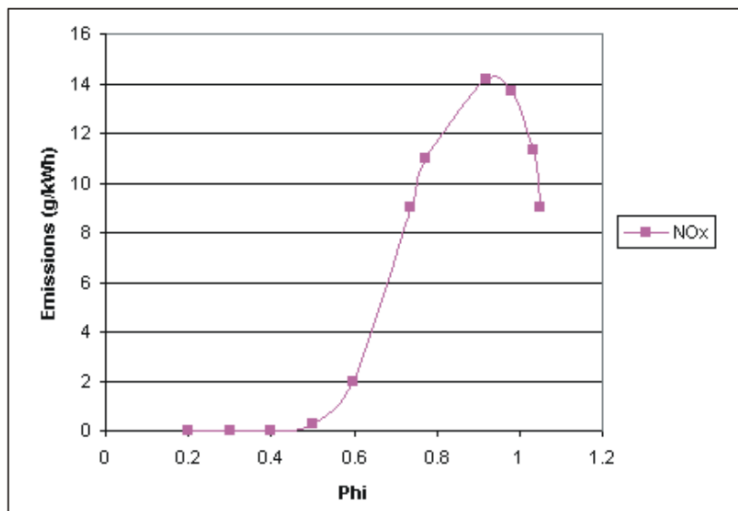


Figure 5 H₂ICE Emissions (College of the Desert, 2001)

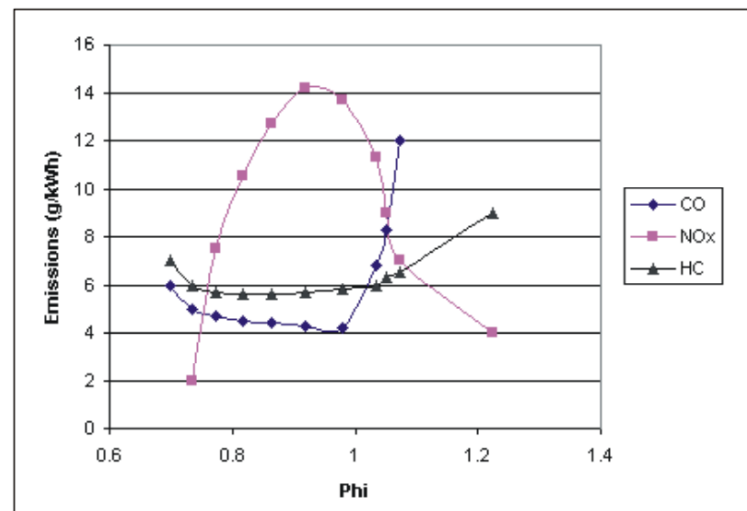


Figure 6 Petrol ICE Emissions (College of the Desert, 2001)

Literature states that all of the special combustion characteristics of hydrogen; Lean burn operation, high flame speed, wide flammability range, high mass-specific energy content, zero carbon and great diffusivity levels (*Appendix 9.4*), when properly exploited can enhance flame stability at the low temperatures capable of limiting NO_x formation (Therkelsen, 2016).

Research shows that H₂ICE engines have been thoroughly reviewed by many and studies reveal that ultra-lean combustion, for example an equivalence ratio of 0.5, is an effective means for minimizing NO_x emissions (Shivaprasad, 2018). Although, other sources state that the richer the hydrogen-air mixture is (but still during lean-burn $\phi < 1$) the higher the power output, and the leaner the engine the lower the power output, thus a compromise must be met. Furthermore, there are other methods of reducing NO_x emissions in a H₂ICE, the University of California carried out tests on a hydrogen powered 4-cylinder, 2L Ford engine on a dynamometer, tests were carried out for a lean burn strategy, but tests were also conducted with a stoichiometric hydrogen-fuel ratio whilst utilising an exhaust gas recirculation (EGR) system. The tests found that if NO_x emissions were not taken into consideration the lean-burn strategy produced more torque than the EGR method. However, if the NO_x emissions needed to be considered and kept to a minimum (for the study this was <10 PPM), then the stoichiometric-EGR strategy could produce nearly 30% more torque (Shivaprasad, 2018). Additionally, another paper consisted of a study which carried out the same tests; lean burn and stoichiometric-EGR strategies, this time on a single cylinder CFR 612CC, a diagram of the test-rig can be found below.

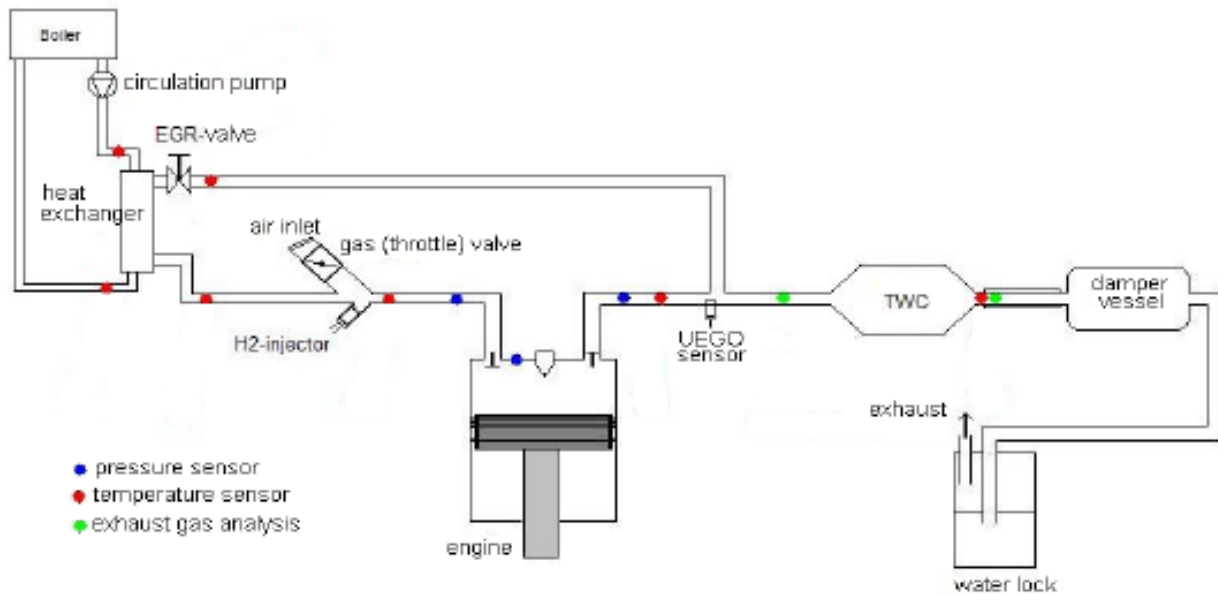


Figure 7 Hydrogen CFR Test Rig (Verhelst, 2003)

The test results from the paper can be seen in Figure 8 on the following page, where the engines power and efficiency for both strategies are plotted as a function of the hydrogen consumption. The graph demonstrated that the higher the fuel rate, the higher the load condition of the ICE. Additionally, for the lean-burn strategy this corresponds with a richer hydrogen-fuel mixture (still on the lean side of the air-fuel ratio), and for the EGR strategy it corresponds with a lower level of EGR. On the other hand, it shows that as the amount of EGR increases or as the engine's combustion becomes leaner the efficiency increases, as to be expected.

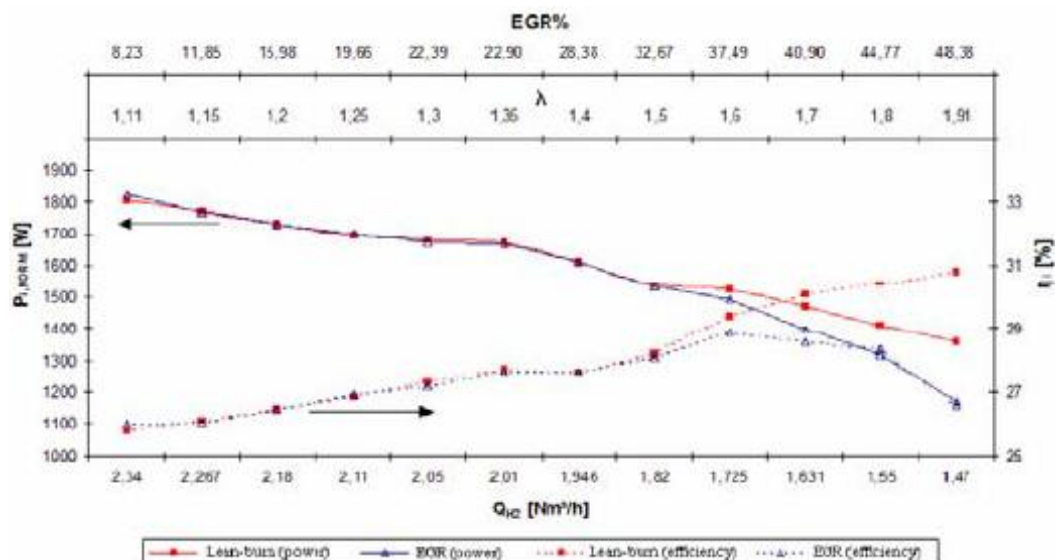


Figure 8 CFR Test Results (Verhelst, 2003)

It is worth noting that efforts have been made in the world of automotive engineering to reduce NO_x emissions by modelling supercharged hydrogen engines combined with EGR with results proving

successful (Wallner, 2009) & (Shivaprasad, 2018), but this strategy will not be considered for the project as the KTM Moto3 engine is N/A, although further work could include the feasibility of turbo or supercharging the engine.

Finally, there are other challenges for H₂ICE's such as its low density and small quenching distance, please see appendices 9.7 & 9.8 for information on these.

3.3 Fuel Delivery System

The ensuing figure shows the different ignition strategies based on the two main injection strategies used in H₂ICE's: Port fuel injection (PFI) and Direct Injection (DI). The KTM Moto3 used in this study is a spark ignition (SI) engine, therefore this will be the only ignition strategy considered within the project.

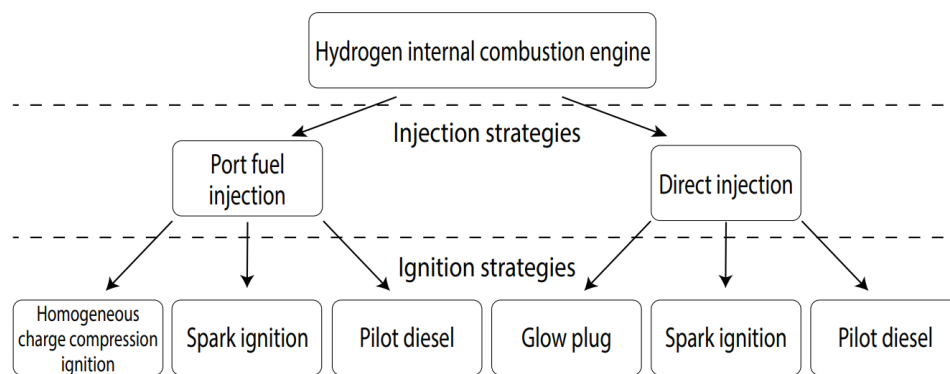


Figure 9 Categorization of Hydrogen ICE Based on Injection & Ignition (Ho Lyung Yip, 2019)

3.3.1 Port Injection



Figure 10 Hydrogen Port-Injection (Anstrom, 2014)

Literature has found that a Hydrogen PFI-SI engine is one of the most investigated modes of H₂ICE and is employed in a variety of variations that differ in multiple aspects such as part-load control, hydrogen-air ratio and charging strategy (Wallner, 2009).

Port injection works by a method of injecting fuel into the intake port upstream of the intake valve during the intake stroke (Ho Lyung Yip, 2019). This is because conditions at that point of the four-stroke cycle are less severe and thus, this method reduces the chances of pre-ignition, there is also there less hydrogen or air in the cylinder at any one time further reducing the odds of pre-ignition (College of the Desert, 2001). in a PFI-SI engine, the method of injecting the air separately also dilutes the hot residual gasses and cools any hot spots, which as previously stated is a problem with H₂ICE's. On the downside, as a result of the lower volumetric energy density of hydrogen a PFI-H₂ICE has a power deficit of around 15% compared to a petrol engine (Verhelst, 2003), there

are options to reduce this deficit including a lean-burn operation which will play a major part in the proposed project to find optimal performance and emissions.

3.3.2 Direct Injection

Direct injection hydrogen is viewed as one of the more attractive options to avoid combustion anomalies and to increase the power density of H_2ICE 's whilst also achieving near-zero emissions (Das, 2016). Also, extensive research has been carried out by BMW since the late 1970's on port injection in H_2ICE 's and found that at stoichiometric combustion, with external mixture formation, hydrogen displaces approximately 30% of the aspirated. Concluding this research BMW suggested that a DI of hydrogen at crank angle 40° - 60° before TDC to the combustion chamber would allow the H_2ICE to have the greatest power density (Shivaprasad, 2018). Therefore, based on this study by BMW, DI of hydrogen theoretically could increase engine efficiency whilst decreasing emissions without sacrificing power.

Direct injection mixture formation strategies is split into three classifications: Wall-guided, Air-guided & Spray-guided as shown in the subsequent figure.

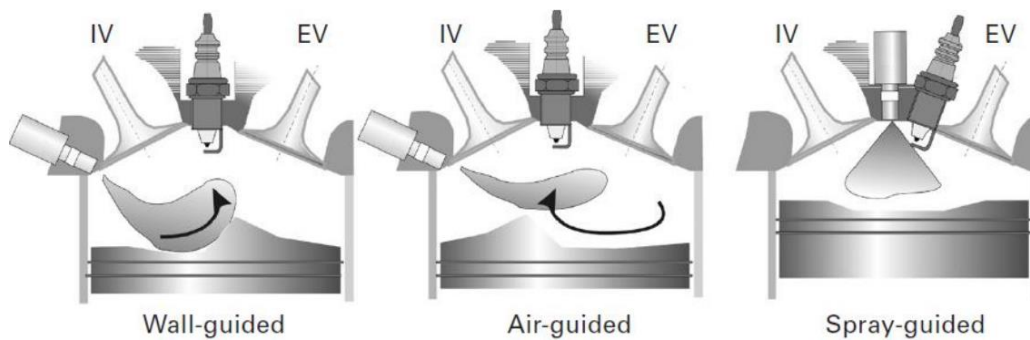


Figure 11 Direct Injection Strategies (Rahman, 2018)

Dependant on the start of ignition the difference between early and late DI can be determined, Figure 12 on the following page visually demonstrates the different DI strategies and their respective timings. The injection timing controls the preignition problem, to both minimise the amount of time that a combustible mixture is exposed to hot spots within the cylinder and also allows for improved mixing of the intake air with the residual gases (Rahman, 2018).

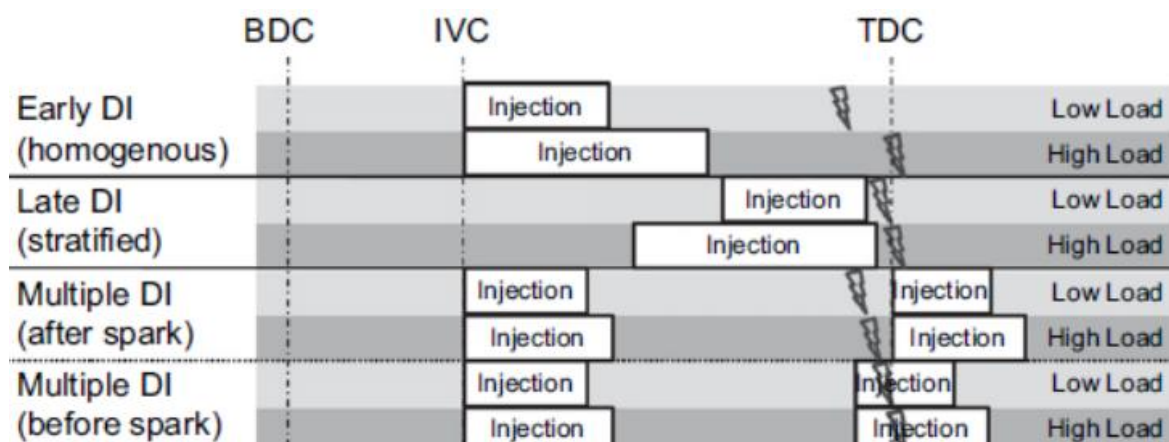


Figure 12 DI Timing (Rahman, 2018)

A DI-H₂ICE can yield peak efficiencies of almost 43% which is close to the highest efficiency of diesel engines, and according to literature is approaching the practical efficiency range of current fuel cell design, whilst using the much less expensive SI-ICE technology (Anstrom, 2014). Studies have also found that the power output of a DI H₂ICE is 20% more than petrol (College of the Desert, 2001).

Finally, it is worth noting that the fuel rail utilised in a DI system will require a higher fuel pressure and also, because of the reduced mixing time of the hydrogen-air ratio in DI the mixture can be non-homogenous, studies have found that this can theoretically result in higher NO_x emissions in comparison to PI strategies (College of the Desert, 2001), this is something that will be considered during the project.

4 Methods

The project is purely a feasibility study and will be completed computationally utilising computer-aided engineering (CAE), three CAE software packages are to be used in order to complete the study; SolidWorks, MATLAB & Ansys Forte. CAE is used to assist engineers and consists of the subsequent three steps:

1. Pre-Processing

The geometry is modelled, and the physical properties of the design alongside applied loads or constraints.

2. Solving

The model is solved using an applicable mathematical formulation of the elemental physics.

3. Post-Processing

The outcome is conferred with the engineer

(Hill, 2020) & (Siemens, 2020)

4.1 CAD Modelling

When the required components have been removed from the Moto3 engine their geometries will be measured and then computationally modelled using computer-aided design (CAD). Furthermore, once the model is complete the parts will be re-measured and validated against the model to ensure no mistakes were made and any deviations from the true components can be altered.

The purpose of CAD is to aid in the design process of a component and to improve the quality and level of detail in a design. Also, CAD lowers production costs for designs and also allows quicker project completion, improving the efficiency of workflow during the design process (Chai, 2021).

The CAD software available on site is Solidworks, a CAD & FEA modelling software package published by Dassault Systems. When all of the components have been modelled, they will then be packaged in assemblies, representing their true operational conditions. Furthermore, based on the MATLAB data the modifications necessary for optimal performance, for example changing the bore, stroke etc will be implemented into the CAD model for use in a motion simulation giving a visual representation of the Moto3 H₂ICE.

4.2 Mathematical Combustion Modelling

4.2.1 Cylinder Pressure & Volume Calculations

The KTM Moto3 cylinder pressure taking combustion into account & cylinder volume will be determined using the following equations:

$$P_2 = P_1 \left(\frac{v_1}{v_2} \right)^n + \frac{dQr(\gamma - 1)}{v_2}$$

Equation 3 Cylinder Pressure with combustion

$$v = vol_{clearance} + \frac{\pi \times Bore^2}{4} \times s$$

Equation 4 Cylinder Volume

Unfortunately, there is no available real-world cylinder pressure or volume data in order to validate the calculated pressure data, and it is not feasible to collect this data with real-world testing on a dynamometer as the rest of the components required to run the engine on hydrogen on a dynamometer is not accessible to the author and also there is the implications of the COVID-19 pandemic. Therefore, another method of validation is required, fortunately there is cylinder pressure data available for a Ford Fox and Ford Sigma engines, the parameters of both these engines will be used in Equation 3 and Equation 4 and then compared to the real-world data. If the calculated data and real-world data is a complete correlation, then this proves as validation and the equations will be used to determine the cylinder pressure and volume data of the Moto3

With the use of MATLAB, a comprehensive data set determined from the calculated cylinder pressure and volume data will be generated covering a full 720° cycle covering all four strokes: intake, compression, expansion & Exhaust. This will be done over an RPM range of 1500-13,500RPM. These calculations will be carried out for two different models of the Moto3, a petrol version and a hydrogen version, for use in a comparative analysis.

Finally, two H₂ICE NO_x models will be made and assessed in MATLAB, an ultra-lean burn engine strategy and a stoichiometric-EGR strategy, a comparative analysis of the two will be undertaken determining which method is the most effective to in reducing emissions without compromising optimal performance outputs for the Moto3 engine.

4.2.2 ANSYS Forte

To investigate the combustion characteristics of the H₂ICE powered Moto3 whilst considering; the fuel injection strategy, ignition timing, spray characteristics and combustion chamber geometry, ANSYS Forte will be utilised.

ANSYS Forte, is a computational fluid dynamics (CFD) software package that is used for modelling ICE's, it incorporates the proven ANSYS Chemkin-Pro solver technology for gas phase and surface chemistry (ANSYS, 2021). Forte is widely recognised as a trusted and accurate simulation solution for modelling in-cylinder combustion, the US Environmental Protection Agency have been using Forte since 2014, allowing them to experiment with engine design in a virtual setting (Green Car Congress, 2014), saving on time and wasted resources involved with physical testing. Additionally, ANSYS' meshing capabilities further reduce the time and effort required to yield highly accurate results, as meshing is something that usually takes a considerable amount of time, but ANSYS aids in reducing this by utilising more automated meshing tools (ANSYS, 2021).

Within the scope of this project, Forte will be utilised as a means to investigate two different SI injection strategies; port injection and direct injection, both for the ultra-lean model and for the stoichiometric-EGR model, whilst also incorporating other combustion and engine design characteristics as previously discussed to evaluate their effects on the flame propagation within the cylinder, as well as performance and emissions. Finally, for the same reasons previously stated, initially the Forte model will be carried out utilising a petrol version of the engine before hydrogen for use in a comparative analysis.

5 Results

The majority of the data to be obtained as part of the proposed project will be of a quantitative nature. For example, the CAD model of the Moto3 engine, which will be validated against the known dimensions and tolerances of the real-life engine. Furthermore, the cylinder pressure data, NO_x model and CFD model will be validated against previously carried out investigations and projects by the author and also from gathered research, technical papers, and investigations of a similar nature. Additionally, there will be an aspect of qualitative data within the project that will be gathered during the initial concept and research phase, consisting of market research on current developments, studies, and existing technology.

The MATLAB model will generate numerical data that will be analysed, this will include the following.

- Change in volume and pressure
- Log Pressure and Volume
- Polytropic Index
- Power, Force & Torque
- Cylinder temperature with and without combustion

➤ NOx Parts Per Million Results

Finally, the CFD results from ANSYS Forte will use a 3D graphical display, which will make determining trends and anomalies within the data sets easier, the CFD results will show how the combustion characteristics as well chamber geometries effects the flame propagation with a visual aid as demonstrated in Figure 13.

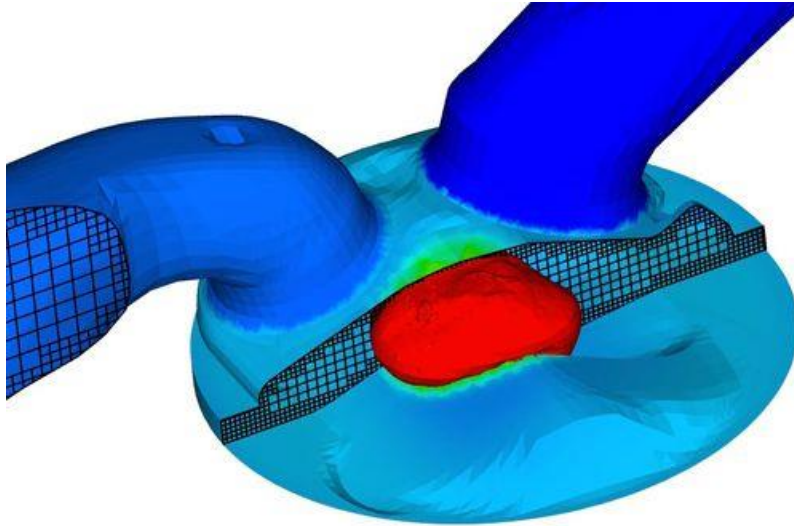


Figure 13 Forte Flame propagation (Green Car Congress, 2014)

6 Project Timescale

The subsequent figure displays a plan of the proposed projects initial timeframe, this plan is not very detailed as it is only a preliminary idea and a better scope and understanding of the required time for certain tasks, will be better known when the project has started.

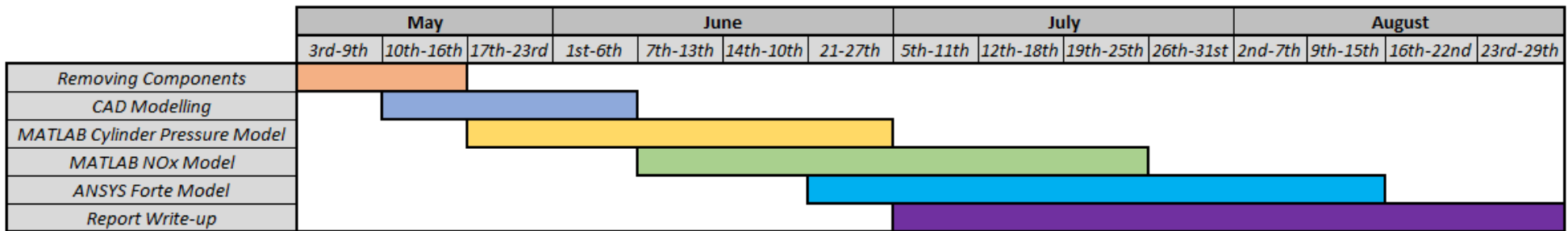


Table 2 Preliminary plan

7 Evaluation

The proposed project is evidently a popular, current, and relevant research area with significant importance in the field of motorsport engineering. As stated throughout this paper, the depletion of fossil fuels, stringent emission regulations and the aim to become carbon neutral within the next decade, means the race to find an alternative fuel is of utmost importance. The literature assessed within this paper aids as a starting point to the project, by using methods that have already been widely used within this research area, meaning that the results gathered from the study can be added to the already existing data and knowledge within that subject area.

The proposed project is not without its limitations. For example, the low density of hydrogen proves problematic when it comes to storing the required amount of the fuel for long-distance trips/races, this is explained in more detail in Appendix 9.7. Furthermore, the most problematic area within the proposed project is the limited resources and facilities as a result of the ongoing pandemic, which generates a lot of uncertainty on whether or not the facilities will be available throughout the duration of the project. A further weakness of the project is that as previously mentioned there is not any readily available real-world cylinder pressure data for the Moto3, unfortunately it is not feasible to gather data using the engine dynamometer as there are other necessary components which the author does not have access to such as an ECU, fuel storage and delivery etc. Consequently, this is the reason the proposed study is a computational feasibility study.

Finally, it is worth noting that the project is to be treated as a means of investigating the feasibility and concepts that have limited published information, thus, there is no distinctly formed theory surrounding the scope of the research, allowing the calculated data to be the main focus of the work.

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9 Appendices

9.1 Appendix 1: Properties of Hydrogen

Molecular weight	2.016
Density @ NTP	Gas: 0.0838kg/m ³
Boiling temperature	-252.8 C
Freezing temperature	-259.2 C
Viscosity of gas @ NTP	8.9 x 10 ⁻⁵ g/cm-s
Diffusion coefficient in still air @ NTP	0.61 cm ² /s
Flammability in air	4 ~ 75 % (volume)
Minimum ignition energy	0.02 mJ
Minimum auto-ignition temperature @ stoich	858 K
Adiabatic flame temperature in air @ stoich	2318 K
Burning velocity	270 cm/s
Lower calorific heating value	120 MJ/kg
Octane number	130 ⁺

Table 3 Properties of Hydrogen (Xiaoguo Tang, 2002)

Table 2-1 Properties of Hydrogen and hydrocarbon fuels

Properties	Hydrogen	Gasoline	Methane
Molecular weight, (g/mol)	2.016	~107	16.043
Density, (kg/m ³)	0.08	~750	0.65
Mass diffusivity in air, (cm ² /s)	0.61	0.05	0.16
Kinematic viscosity, (mm ² /s)	110	1.18	17.2
Stoichiometric volume fraction, (in air)	29.5	1.65	9.5
Minimum ignition energy, (mJ)	0.02	0.25	0.28
Minimum quenching distance, (mm)	0.64	~2.0	2.03
Flammability limits in air, (vol%)	4-75	1.0-7.6	5-15
Flammability limits, (φ)	0.1-7.1	0.7-3.0	0.5-1.67
Burning velocity at NTP air, (cm/sec)	265-325	37-43	45
Auto-ignition temperature, (K)	858	501-744	813
Adiabatic flame temperature, (K)	2390	~2275	2225
Normalized flame emissivity, (200K, 1atm)	1.0	1.7	1.7
Stoichiometric air-to-fuel ratio, (kg/kg)	34.2	14.7	17.1
Lower heating value, (MJ/kg)	120	45	50
Higher heating value, (MJ/kg)	142	48	55.5

Table 4 Properties of Hydrogen and Hydrocarbon Fuels (Rahman, 2018)

9.2 Appendix 2: Internal Combustion Engine

The concept of the ICE is that an air-fuel mixture is fed to the inside of the cylinder where it is compressed and then burnt. This combustion releases heat energy, the high gas pressures generated force the piston to move along its stroke within the cylinder, thus, converting the heat energy into useful mechanical work (Heisler, 1999). The 2014 KTM RC250R engine to be used in the study is a single cylinder 250CC naturally aspirated SI engine utilising a four-stroke cycle consisting of intake, compression, expansion, and exhaust strokes as demonstrated in the following diagram.

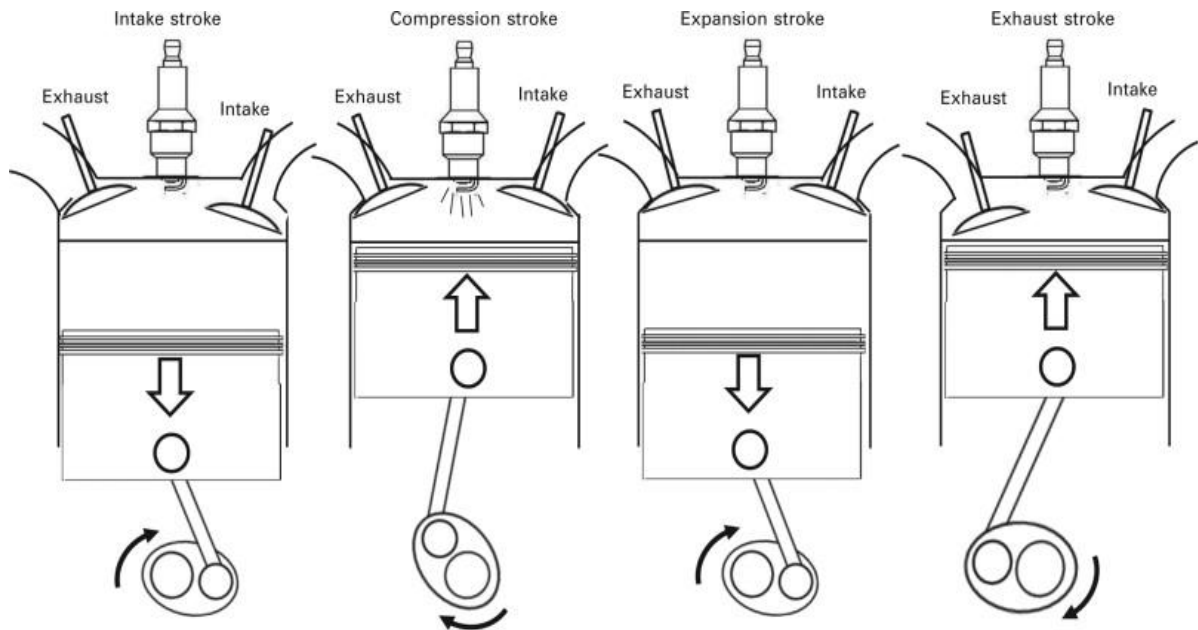


Figure 14 Four-Stroke Cycle (Johnson, 2014)

9.3 Appendix 3: Otto-Cycle

When considering a reciprocating SI engine, the Otto cycle is the theoretical cycle of interest and was introduced by Nikolaus Otto in the late 1800's after he demonstrated the four-stroke SI engine effectively (Proctorll, 2003). The ideal Otto cycle can be seen in Figure 15, and is made up of the following processes:

- **1-2;** Isentropic compression of the working fluid. takes place as the piston travels from BDC to TDC.
- **2-3;** Constant volume heat addition.
- **3-4;** Isentropic expansion of the working fluid producing useful work.
- **4-1;** Constant volume heat rejection.

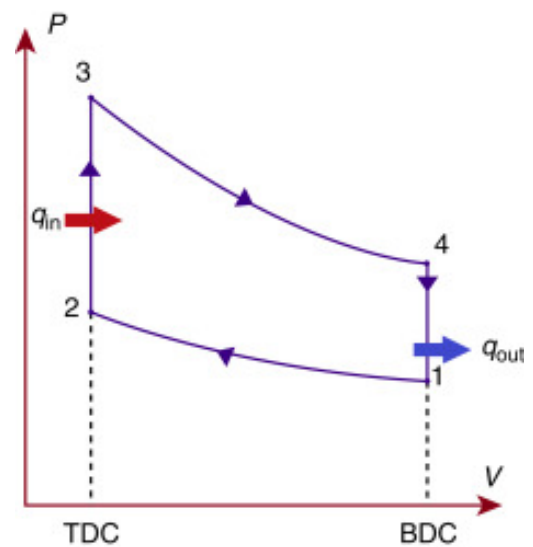


Figure 15 Otto-Cycle (Demir, 2018)

(Proctorll, 2003) & (Demir, 2018).

9.4 Appendix 4: Flame Temperatures

A study carried out by Ford in 2002 developing a P2000 hydrogen engine dynamometer stated that the adiabatic flame temperature in air at stoichiometric for hydrogen is 2318 K (Xiaoguo Tang, 2002), another study stated that adiabatic temperature for petrol is 2275 K (Rahman, 2018).

9.5 Appendix 5: Compression Ratio

The compression ratio is defined as the ratio of the total volume of the cylinder when the piston is at BDC to the total volume of the combustion chamber when the piston is at TDC. Literature states that theoretically, increasing the compression ratio can in-turn improve the thermodynamic efficiency of an engine by producing more power (Aina T, 2012). Furthermore, another reason that a H₂ICE can utilise a higher compression ratio compared to a petrol engine is because the limit of the compression ratio of an ICE is based on the fuel's resistance to knock and a lean burn H₂ICE is less prone to knock than an ICE powered on petrol.

9.6 Appendix 6: High Diffusivity

Petrol has a mass diffusivity in air of 0.05 cm²/s whereas the mass diffusivity of air of hydrogen is 12.2 times greater at 0.61 cm²/s (Rahman, 2018). From a safety point of view, the rapid dispersion rate of hydrogen is its greatest safety asset if a hydrogen leak were ever to occur (Singh, 2015).

9.7 Appendix 7: Storage Problems

Hydrogen is the most abundant and explosive gas on earth, but also the lightest with a molecular weight of 2.016 g/mol (National Center for Biotechnology Information, 2019), compared to that of petrol which is usually between 60 and 150 g/mol (Mauriello, 2019). Hydrogen then, has a very low density and at 20.15K and 0.1 MPa liquid hydrogen has a density of only 71 kg/m³ (Bimbo, 2019), as opposed to the much higher density of petrol which is 715-780 kg/m³ (ToolBox, 2003). Consequently, this means that to provide a vehicle an adequate driving range a large volume tank is required to properly store the necessary hydrogen. In a paper titled "*Hydrogen-Fuelled Internal Combustion Engines*" from 2009 it was stated that hydrogen has a very low energy density in comparison to other fuels in use today, even when compressed to 700 bar or liquefied, both of which incur substantial energy losses (Wallner, 2009). As discussed previously, the proposed project aims to investigate purely the combustion modelling side of a H₂ICE so this issue will not be investigated, however this is a hot-research area currently especially at companies such as FEV and has potential for a research project or further-work.

9.8 Appendix 8: Small Quenching Distance

The quenching distance is defined as the distance between two parallel plates that will extinguish or "*quench*" the flame front of a particular oxidant-fuel mixture (CPS, 2020). Unfortunately, hydrogens quenching distance is smaller than petrol's and therefore, hydrogen flames travel closer to the cylinder wall before they are quenched (College of the Desert, 2001). Studies have been done to investigate

affects the quenching the distance of hydrogens flames to see if they can be improved. A study titled *“Prediction of Burning Velocity and Quenching Distance of Hydrogen Flames”* computationally with the use of ANSYS Forte, investigated atmospheric, laminar, stoichiometric, pre-mixed hydrogen-air flames in a diverging channel for the prediction of the quenching distance and its effects (Pfeiffelmann, 2019).